FINAL REPORT - 1992

THE SANTA CLARA VALLEY WATER DISTRICT WEATHER RESOURCES MANAGEMENT PROGRAM

A SUMMARY OF CLOUD SEEDING ACTIVITIES CONDUCTED OVER THE TOTAL DRAINAGE BASINS UPSTREAM FROM ANDERSON AND COYOTE RESERVOIRS DURING THE PERIOD 1 FEBRUARY 1992 - 30 APRIL 1992

Report Prepared for

The Santa Clara Valley Water District
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San Jose, California 95118-3686

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WATER DISTRICT
5750 Almaden Expressway
San Jose, California 95118

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THE SANTA CLARA VALLEY WATER DISTRICT
WEATHER RESOURCES MANAGEMENT PROGRAM

EXECUTIVE SUMMARY

Cloud seeding programs designed to increase rain and snow have been conducted in California for the past 44 years. Three or four programs have been operated every year for 25 to 40 of those years. During the 1991/92 water year, there were 20 such programs active in the state. Among these was the Santa Clara Valley Water District (SCVWD) program conducted by Atmospherics Incorporated to increase precipitation over the drainage basins upstream from Anderson and Coyote Reservoirs. The program components included a ground-based radar system installed at the Santa Clara County Communications Center, a turbocharged twin engine cloud seeding aircraft based at the San Jose Airport, an experienced radar meteorologist and cloud seeding pilot assigned to the program, and a satellite weather data acquisition system plus support personnel and equipment at AI's head office in Fresno.

Personnel and equipment were on a standby alert 24-hour-per-day, seven-days-per-week operations schedule during the period 1 February 1992 through 30 April 1992. Seedable clouds and storm systems which affected the target area were logged on 13 days during this 3-month operational period. The program was temporarily suspended from 1800 on 14 February until 0530 on 15 February when the NWS issued a "Flash Flood Warning". Two seeding opportunities were missed during this period. As a part of operations, the supervising radar meteorologist plotted a total of 296 precipitation echoes on 116 radar overlays for purposes of documenting the clouds and storm systems. The cloud seeding pilot logged 31.3 hours during the 19 aircraft flights. A total of 163 cloud seeding devices were ignited, dispensing 3,260 grams of silver iodide.

The radar information was used to compare a number of important rainfall characteristics between seeded and non-seeded clouds and storm systems within the operational area and beyond the effects from seeding. From this study, the four major parameters of maximum echo intensity, maximum echo height, duration of precipitation period, and areal coverage of precipitation indicate increases in the range of 5% to 41%.

When one applies the standard radar equations to the reflectivity data, there is a strong indication the cloud seeding program operated during the 1991/92 period did produce an increase in precipitation in the range of 9% to 13%. This is nearly two inches of additional precipitation at ground level. How this extrapolates to additional streamflow has not been determined at this time. However, if similar hydrologic investigations in other coastal and nearby mountain areas of California apply to the drainage basins upstream from Anderson and Coyote Reservoirs, the increase in streamflow due to the cloud seeding program could be in the range of 1900 to 2800 A.F. during the 1991/92 water year. Further hydrologic studies on this aspect are in progress.

The apparent results noted above, as derived from radar data analyses, precipitation data, and hydrologic studies, are intentionally reported on the conservative side. The actual increases in precipitation and water supplies produced by the cloud seeding program may well be somewhat higher than these figures.

A summary of aircraft operations during the 1991/92 season is shown in Table 1.

TABLE 1.

AIRCRAFT OPERATIONS SUMMARY

		2/1-4/30 1991/92
1.	Seeding flights	19
2.	Hours	31.3
3.	Cloud recon. flights (no seed)	-
4.	Hours	-
5.	Total flights	19
6.	Total hours	31.3
7.	Total pyrotechnic seeding devices	163
8.	Silver iodide (gms)	3260

ATMOSPHERICS INCORPORATED
FRESNO, CALIFORNIA

THE SCVWD WEATHER RESOURCES MANAGEMENT PROGRAM

1.0 INTRODUCTION

Modern cloud seeding efforts for the purpose of increasing rain and snow over numerous areas in California began with a few landmark programs in the late 1940's and early 1950's. Some of these early projects, along with the initial year of operation, can be listed as follows:

- The California Electric Power Company program over the Bishop Creek watershed of the eastern Sierra, (1948).
- The Southern California Edison Company program over the Upper San Joaquin River Basin, (1950).
- The Pacific Gas and Electric Power Company Program over the Lake Almanor Watershed (1953).
- The Kings River Conservation District program over the Kings River Watershed above Pine Flat Dam, (1954).

During the 1991/92 winter season, there were 20 cloud seeding programs conducted in California. Atmospherics Incorporated presently conducts 11 of these programs. These range from the most northerly location over the Anderson and Coyote Reservoirs drainage basin as conducted for the Santa Clara Valley Water District to the most southerly activity conducted for the City of San Diego over the higher mountain reservoir areas east of the city.

The subject of cloud seeding is not new to the SCVWD. Beginning in the late 1950's, a program was initiated over Santa Clara County. This program was active for several years and substantial evaluations strongly suggested positive results. In mid-1991 the modern technology of cloud seeding again came under investigation by the SCVWD. This action was prompted by the increasing demands for both urban and rural water supplies, present statewide drought conditions, and the desire of SCVWD to explore all possible solutions to this ongoing crisis. As this study evolved, Atmospherics Incorporated received notification that it would ultimately conduct the proposed program.

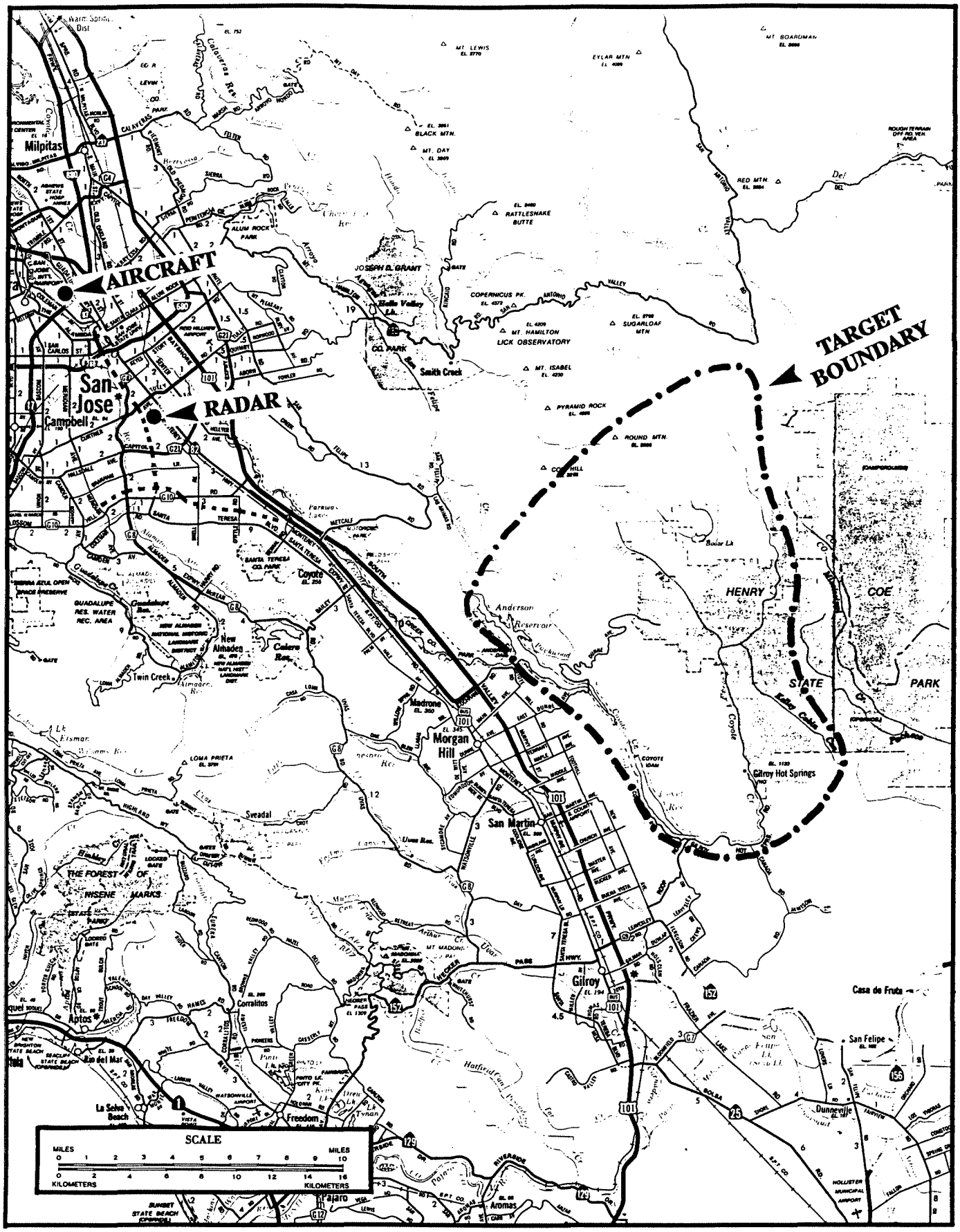
A review of the District's previous environmental study, plus other administrative activities evolved and it was concluded that no significant detrimental effects on the environment would be produced by the proposed weather resources management program. Under present statutes in California a Negative Declaration was filed. Operational procedures were identified and a contract was signed for an active program beginning on 1 February 1992 and ending on 30 April 1992. The weather radar system was activated at the County Communications Center location and the aircraft was positioned at the San Jose Airport.

The program was fully operational on 27 January 1992. This final report summarizes the overall operations during the period 1 February 1992 through 30 April 1992.

A map of the operational area is shown in Figure 1.

FIGURE 1.

THE SCVWD WEATHER RESOURCES MANAGEMENT PROGRAM OPERATIONS AREA -- 1991/92 SEASON



2.0 PHYSICAL BASIS FOR SEEDING CLOUDS

Cloud seeding as a method for modification of precipitation mechanisms started in the late 1940's after Nobel Laureate Irving Langmuir and his colleagues Drs. Vincent Schaefer and Bernard Vonnegut, working at the General Electric Research Laboratory in Schenectady, New York, first began earnestly seeking answers to complex questions about the basic nature of precipitation processes. As a result of past research and applied programs over many areas of the world, answers have been provided to many of these questions. The concept that cloud seeding can be practically used for beneficial purposes at favorable benefit/cost ratios, has gained considerable scientific acceptance and is rapidly expanding at international levels.

The various physical and chemical properties, plus the interrelated mechanisms which come together to produce clouds and precipitation, are complex and not fully understood. However, the many investigations conducted over the past 40 years have illuminated a number of fundamental concepts as well as produced many specific insights to this complex array of static and dynamic properties. The scientific foundation of glaciogenic seeding for precipitation enhancement rests upon a few simple physical principles and two postulates.

Most of the natural precipitation in middle latitudes begins as ice crystals in supercooled clouds. Supercooling is the condition of cloud droplets remaining liquid at temperatures colder than 0°C (32°F). It is a common condition in both convective and stratified clouds down to temperatures of about -20°C (-4°F). The cloud droplets are formed around microscopic particles such as dust, smoke, and salt crystals. Scientists classify these particles as cloud condensation nuclei (CCN) and without them there would be no clouds. The relative sizes of cloud droplets and particles are important considerations even within a simplistic understanding of precipitation mechanisms. Continental cloud droplets are small, around 10-15 microns diameter. This means it requires about one million cloud droplets to produce a single raindrop!

Among the total atmospheric particulates, there are a few special kinds known as ice nuclei (IN), on which cloud droplets freeze or ice crystals form and grow directly from the water vapor phase. As a general rule, in the atmosphere there is an abundance of condensation nuclei which nature can use to produce cloud droplets, given the proper temperature and humidity regimes. However, there is often a scarcity of the special ice nuclei required to initiate the "cold-cloud" precipitation process.

An ice crystal in the presence of supercooled cloud drops will grow by vapor deposition as nearby drops evaporate, because the saturated vapor pressure over ice is less than that over supercooled liquid at the same temperature. In this way a crystal can gradually acquire the mass of many cloud droplets. This allows it to fall through the cloud, growing by collision with some of the cloud droplets, ultimately reaching the ground as a precipitation particle. Additionally, the growth of ice from supercooled cloud droplets releases latent heat of fusion, which augments cloud buoyancy.

The variability of all nuclei types, sizes, concentrations and chemical composition definitely influences the ability of nature to produce a cloud and subsequently to produce precipitation from that cloud. Additionally important in the precipitation processes are the physical sizes (vertical and horizontal), the growth rates, the liquid water content and the overall lifetime of clouds. These various parameters can come together in almost infinite combinations to form precipitation over much of the world by a process often described simply as the "cold cloud" process.

From all of this, the first postulate of cloud seeding states that the precipitation efficiency of some clouds is limited by a shortage of natural ice nuclei effective at the extant cloud temperatures. Adding artificial nucleants to these clouds can enhance the precipitation process and increase precipitation on the ground. The second postulate states that increased buoyancy, resulting from seeding-induced conversion of supercooled cloud droplets to ice crystals, will invigorate cloud updrafts. This will enable clouds to grow larger, process more water vapor and yield more precipitation.

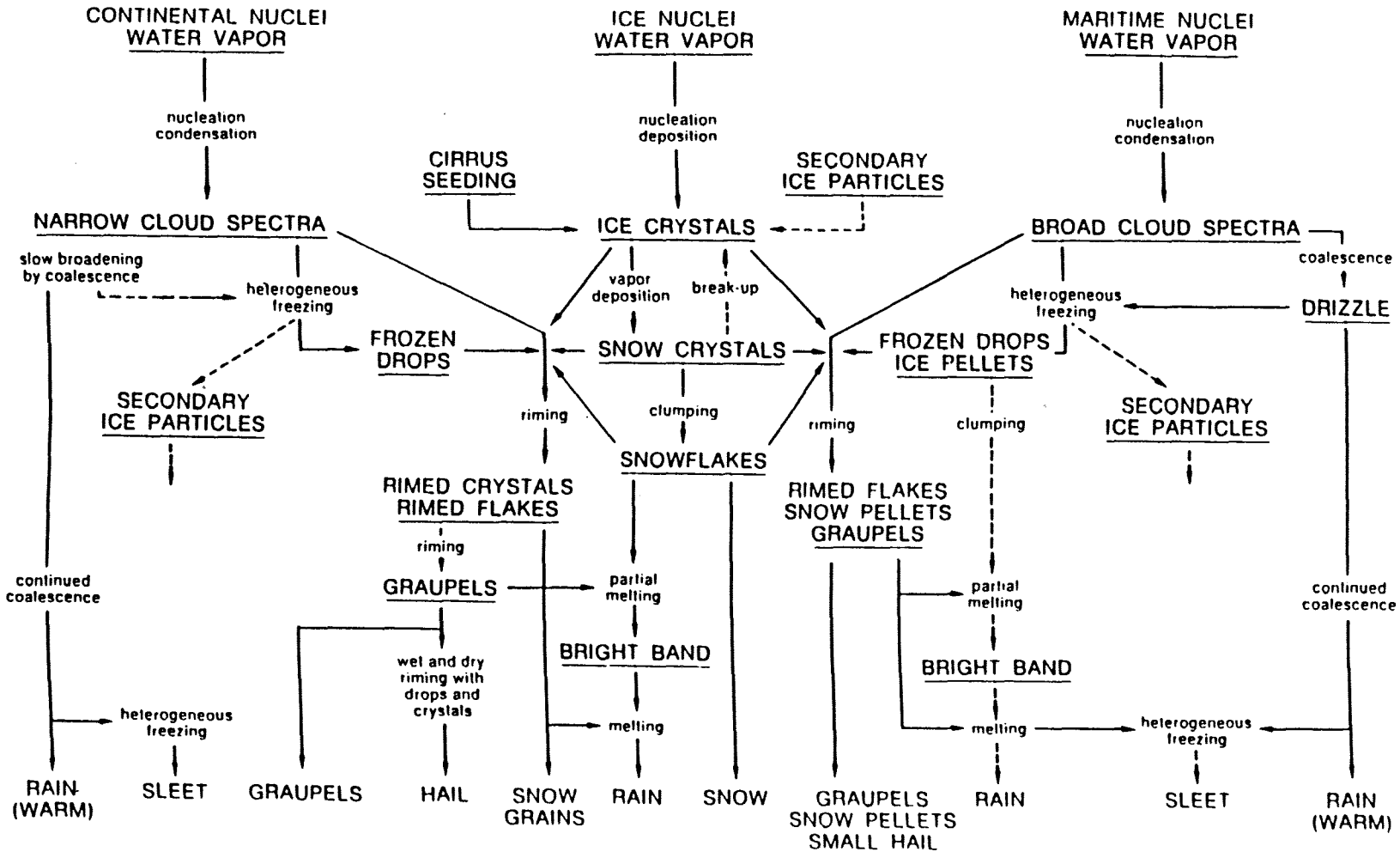
A more detailed description of the interacting forces is not relevant to this report. There is an adequate supply of information in the scientific literature for those who wish an in-depth treatment. For this summary, it is enough to understand that under certain cloud temperature conditions the rate of water consumption for ice crystal growth is less than the rate at which water condensate becomes available to the cloud. When this condition is present, and there is a deficiency of ice nuclei active in the cloud temperature range from about 0 °C (32 °F) to -20 °C (-4 °F), opportunities exist for the beneficial addition of artificial ice nuclei. **The technology may best be described as simply lending nature a helping hand.**

Some 98% of all the cloud seeding programs conducted in the United States and 45 other countries utilize silver iodide as the primary artificial ice nuclei. Pure silver iodide crystals are hydrophobic and do not act as condensation nuclei. Contact nucleation or sublimation from the vapor phase are the mechanisms in this case. However, when silver iodide is complexed with other compounds such as sodium iodide, ammonium perchlorate, sodium chloride or sodium perchlorate, the resultant complexed particles are hydrophilic and the nucleation process in this case is condensation followed by freezing. Condensation can take place around the complexed silver iodide ice nuclei and the cloud droplets will then freeze at some temperature relevant to the specific complexing material.

The various precipitation processes are illustrated in Figure 2.

FIGURE 2

FLOW DIAGRAM OF PRECIPITATION PROCESSES



3.0 DESIGN OF THE PROGRAM

3.1 Program components

Any well organized modern cloud seeding program must include at least a minimum number of basic components which are essential to successful operations. These include:

- Weather data acquisition and forecast system
- Ground-based weather radar system
- All-weather cloud seeding aircraft
- Airborne nuclei dispensing systems
- Communications system
- Team of qualified and dedicated personnel

3.1.1 Weather data acquisition and forecast system

As a minimum, the following weather information is obtained and assimilated each morning from the in-house satellite weather data acquisition system at AI head office in Fresno plus other possible sources at the field headquarters.

- Continental U.S. surface analysis charts locating high and low pressure areas, weather fronts and other developing systems.

- Latest 850 mb, 700 mb and 500 mb constant pressure charts presenting temperature, moisture and windfields.

- Western U.S. radar summary charts locating general precipitation areas and storm systems.

- A reanalysis of public forecasts up to 24-hour periods showing wind, temperature, moisture and vertical velocity for the 850 mb, 700 mb and 500 mb pressure levels over California and surrounding states.

- Atmospheric soundings curves from rawinsonde stations and other special locations when available.

- Enhanced satellite depictions of weather elements over the western U.S. and eastern Pacific regions.

3.1.2 Ground-based weather radar system

For operations within the SCVWD Program, AI installed and operated one of its standard 5cm (C-band) weather radar system. The trailer mounted components were located atop the hill at the County Communications Center near Santa Clara. The radar system operated on a frequency of 5,500 Mhz and incorporated a Planned Position Indicator display (PPI) and Range Height Indicator display (RHI). The chosen displays on the console indicator included ranges of 50, 100, 250, and 400 kilometers. Specifications on the radar included a peak power of 250 kw, sufficient to provide a detectable signal with precipitation rates of 1 mm/hr at approximately 100 kilometers. The two-meter diameter parabolic antenna provided a 2° pencil beam width.

The radar system provided vertical and horizontal measurements including echo heights and intensities as well as the precise location and area coverage of all precipitation. Radar observations of cloud motions were used to update all airborne seeding operations. Also appearing simultaneously on the radar display at any given time was the position of the cloud seeding aircraft whenever its operation was active. After the radar meteorologist identified seedable conditions in the clouds and weather systems, the pilot was directed to one of the cloud seeding flight tracks westerly from the target area. The pilot also relied upon visual identification of cloud characteristics for further seedability determinations. Within the complex rapidly changing storm systems and/or nighttime operations, the radar became indispensable in providing assistance to pilots while locating the preferred seeding areas along the flight track and dispensing the nucleating material.

3.1.3 All weather cloud seeding aircraft

For many years, AI has utilized Piper Aztec aircraft on a number of similar projects in the U.S. including the Kings River, Kaweah River, Kern River, eastern Sierra programs in the Sierra Range of California, the Utah-Idaho program for the State of Utah, the northern California program for the State of California, and the Catalina Project for the Southern California Edison Co. AI owns its own aircraft, and has total control of their use, including equipment installations and any relevant structural modifications. Such installations and modifications might include those which SCVWD or others could, at some point in the future, consider useful for optional measurement instrumentation.

The flight endurance of the Aztec aircraft is approximately five hours. The turbo-charged system allows ascent rates from sea level to 20,000 ft. in less than 30 minutes and a proper cruise speed during seeding applications in the range of 120-150 kts. When configured for seeding flights with all instrumentation, full fuel on board, active seeding devices and equipment, plus pilot and passenger, the Piper Aztec remains below allowable gross weight. The aircraft was equipped with all navigational and communications aids required by the U.S. Federal Aviation Administration for full IFR flights under normal icing conditions.

During the contract period the aircraft was maintained at full readiness on a 24-hour-per-day, 7-day-per-week schedule at the San Jose Airport. Aircraft seeding operations conducted during nocturnal storm periods were considered a routine part of overall

operations, simply because about half the total precipitation in California falls at night. During storm periods all seeding flights were supervised by the radar meteorologist. Additional personnel within the overall AI core staff provided useful inputs to all project operations.

3.1.4 Airborne nuclei dispensing systems

Airborne delivery of artificial ice nuclei was chosen as the preferred method for this SCVWD Project. Two different systems for generating the silver iodide nuclei were installed on the aircraft. The first system for nuclei generation included two special mounting racks installed on the wings, each accommodating a total of 20 solid state seeding devices. These units were electrically ignited from a control box within the aircraft. Because the silver iodide use rate from airborne liquid fuel generators cannot be changed in flight, these solid state devices serve an extremely important function during those weather conditions when larger amounts of supercooled liquid water are encountered.

The backup system included two liquid-fuel silver iodide generators mounted on the wing tips of the cloud seeding aircraft. These were the standard AI airborne generators with a variable use rate capability between 0.5 and 3.0 gallons per hour. When combustion is in progress the units are usually set for use rate of 2.0 gallons per hour of 2% AgI-NH_4I acetone solution. Each airborne generator has a total capacity of 6.6 gallons. Generator tanks, tubing, filters and other parts in contact with the silver iodide solution are constructed of stainless steel. The temperature within the flame chamber in the aft section of each generator is approximately 850°C (1,470°F) when configured for the indicated use rate.

3.1.5 Communications system

AI considers a strong and reliable communications network one of the most important components of any weather modification program. Communication within the SCVWD program was accomplished with Motorola mobile (dual-channel) and base station (dual-channel) units. The primary frequency used on this program was 469.500 Mhz.

The AI communications system was used to coordinate the aircraft seeding flights, project vehicles, and radar activities during all storm periods. A base station was located at the AI radar field headquarters. Mobile units were installed in the aircraft and one of the project vehicles. Further communications involved a FAX system installed at the radar site for purposes of receiving from AI head office, and other sources, the routine daily weather forecasts and subsequent updated weather data necessary for the proper conduct of the program.

3.2 Methods of operation

The basic design of the SCVWD Program was not focused on pure research activities although the data obtained will certainly be beneficial to possible design improvements in

the years ahead. No randomization was concluded in this basic design because of the SCVWD's desire to maximize the enhancement of precipitation. There has been a willingness to accept evaluation uncertainties associated with this purely operational approach. On the other hand, sponsor representatives usually indicated a keen interest in the acquisition of all data which might point the way toward apparent results.

Fundamental to significant precipitation enhancement over the desired target area was the requirement to correctly identify developing clouds and storm systems which have a high potential for producing precipitation. At that point, through airborne application, it was necessary to deliver the required amount of nuclei to the cloud system intended for modification. Equally important, the nuclei must be correctly placed directly within that volume of the storm system which is ultimately responsible for producing precipitation. To accomplish these tasks, a number of daily activities are required. A flow diagram which illustrates the usual AI's daily sequence of operational events is presented in Figure 3.

3.3 Suspension Criteria

As in any well designed and responsibly conducted weather modification program, the SCVWD Program design included basic guidelines for temporary suspension or curtailment of cloud seeding operations under certain conditions. These project safeguards are designed to avoid runoff or reservoir storage beyond manageable limits and to avoid contributing to (or appearing to contribute to) hazardous situations resulting from naturally occurring weather-related phenomena. The basic categories are:

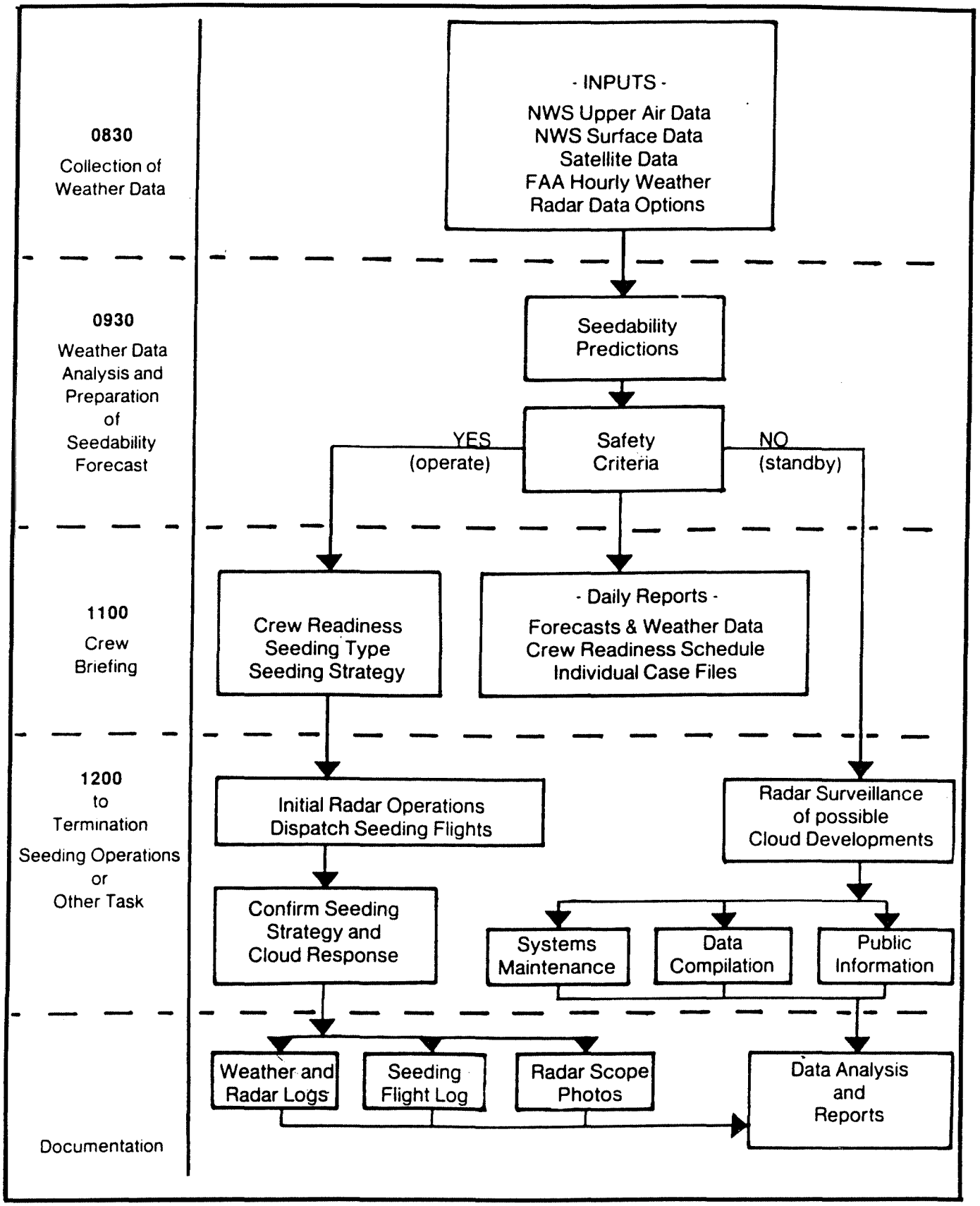
- excess reservoir storage
- total snow/rainfall status
- potential flood situations
- severe weather threats
- other special circumstances

The first category is a SCVWD administrative consideration related to management of runoff from precipitation. Total precipitation status within the second category is usually estimated on a periodic basis using data gathered as part of the normal acquisition of precipitation amounts from such sources as the SCVWD's reporting precipitation gage network, the Department of Water Resources, the National Weather Service, public utilities and other sources. Any discussion of project temporary suspension or termination within these first two categories is initiated by SCVWD personnel, although continually monitored by AI.

Consideration of the other three categories is a routine facet of ongoing forecasting and operational activities conducted by AI, with the decision making time frame within these categories being far shorter than commonly used in periodic rainfall assessments. These factors are monitored on a storm-by-storm basis, and even on a sub-hourly basis during rapidly changing weather conditions. National Weather Service Flash Flood or Severe Weather Warnings will trigger temporary curtailment as appropriate. While curtailment related to severe weather threat, i.e. severe thunderstorms with high potential for damaging

FIGURE 3.

OPERATIONS FLOW DIAGRAM



hail and/or tornadoes, is typically infrequent and short-lived, suspension during potential flood situations might span several days. Special circumstances such as search and rescue missions or other emergency situations within the target area may result in temporary curtailment of seeding operations as deemed prudent.

Within a few of the storm periods, episodes of lightning, hail, tornado warnings, and severe turbulence were noted. During the 1991/92 season none of these episodes were severe enough to require a temporary flight suspension. However, the project was temporarily suspended late on 14 February 1992 because of the NWS "Flash Flood Warning". This warning was cancelled on the morning of 15 February 1992, and the program was returned to full operational status. Two additional seeding flights under reasonably good cloud conditions would have been conducted in the absence of this mandatory suspension criteria.

3.4 Area-of-Effect Targeting Models

For the past 15 years, special atmospheric models have been under development within AI which would allow rapid computer computation of an area targeted by the microphysical response to aerial and ground released artificial nuclei. These models can include conceptual models, microphysical growth models, two-dimensional time dependent models, diagnostic numerical targeting models, and sophisticated three-dimensional nested grid models. Each has a specific role to play in the conduct and evaluation of a cloud seeding program.

Almost all of these models have focused on the production of a vertical curtain of artificially produced ice crystals from falling dry ice pellets or ejectable pyrotechnic seeding devices containing silver iodide. In more recent years, a few have seriously focused on the more complicated problems associated with horizontal lines of seeding material produced by airborne liquid fuel generators and burn-in-place pyrotechnic seeding devices, or produced from fixed point sources of ground based generators in mountain areas. **In any of these cases it is extremely important to recognize that the models require at least two major inputs prior to seeding:**

- an upwind atmospheric sounding which provides data at upper levels on airflow and temperature at the time seeding will commence

- cloud physics measurements of supercooled liquid water and ice crystal concentrations during the seeding events

In the case of the SCVWD Program, no real-time atmospheric sounding data are available immediately upwind (westerly) of the target boundaries at the time of seeding and the program is not funded for expensive airborne measurements of supercooled liquid water and ice crystal concentrations. Of course, windflow direction and velocity at several levels of the atmosphere can be calculated from the radar which provides a large amount of information on storm motions.

Even with the known uncertainties, it is wise to apply some simplistic computerized models

which focus on targeting the seeding effects over the drainage basins of the Anderson and Coyote Reservoirs, as we do on other programs in California and elsewhere in the world. This approach utilizes estimates of windflow (direction and speed) derived in part from radar surveillance of storm motions, temperature profiles from closest available soundings, and confirming measurements from the aircraft on climb-out. Once the flight track is finalized, then the model addresses the conversion of supercooled cloud droplets to ice crystals, the diffusion and growth of these crystals, and finally the fallout trajectory to ground level. All of the model calculations provide not only a simplistic basis for targeting, but for the later analysis of effects.

As our knowledge evolves, and computers increase in speed and capacity, more sophisticated models will be developed. Once these models can be appropriately verified, they could then be applied with higher levels of sophistication in attempts to understand the complexities of flow fields and precipitation mechanisms in target areas. Unfortunately, it is likely these models are still several years away.

3.5 Personnel

The work described in this report requires highly competent, enthusiastic and dedicated personnel, especially those who constitute the core group assigned to any project. The experience and leadership of those core individuals, combined with competent support personnel and supportive home office management, yields highly effective field teams. In this case, the availability of such AI permanently based full-time persons provided strong, important and rapid-response inputs to all aspects of program design, implementation, operations, maintenance and evaluations.

We emphasize the AI concept for provision of personnel includes a strong desire to furnish as many multi-talented people as possible on field projects without producing a "task-overload" for any one individual. This approach has a significant cost-effective aspect and increases the cooperative team spirit during operations. Our people are capable of successfully accomplishing the necessary requirements under more than one task. For example, forecasters may also be computer programmers, meteorologists may be excellent radar operators, electronics technicians are often highly qualified radar specialists and experienced loud seeding pilots may be qualified aircraft mechanics.

Further, the additional number of full-time weather modification employees permanently based at AI head office in Fresno, plus the extensive on-site equipment and spares, provide strong back-up capabilities for, (1) immediate response to maintenance requirements (both preventative and emergency), and (2) depth of personnel and equipment for those "unforseen" requirements which always seem to be a part of any field program.

The three persons directly assigned to the SCVWD Program during the 1991/92 season have logged a total of 912 man-months direct experience in the field of weather resources management.

4.0 OPERATIONS

In most of California, the total streamflow, reservoir storage, and ground-water levels remain well below average. Because of the unusual nature of the storm systems noted during the 1991/92 winter season, many of the coastal areas, including southern California and the adjacent desert areas, recorded above-average precipitation while the snowpack in the higher elevation areas barely exceeded the 50% mark. Although some locations received much-needed rainfall, water-year 1991/92 will definitely go into the record book as the sixth consecutive overall drought year in California. The Palmer Drought Severity Index, which responds slowly and depicts prolonged dryness or wetness, continues to classify a large part of California as being under severe dry conditions.

During the three-month operations period from 1 February 1992 through 30 April 1992, almost all suitable cloud systems affecting the Anderson and Coyote watersheds were seeded. The single exception was the mandatory suspension period from 1800 on 14 February until 0530 on 15 February as prompted by the NWS Flash Flood Warning. Two flights were lost due to this suspension. These mandatory suspension periods are part of the formal suspension criteria as set forth in the operations plan. The criteria are serious attempts to address public safety issues and avoid any possibility of damage perceived to result from the cloud seeding program.

February 1992 was an appropriate month to initiate the SCVWD program. The weather situation dramatically improved from the previous month with 11 seeding flights conducted during the eight seedable days. One was rated excellent, three were rated good, four were noted as fair and three were rated poor. March was not the "Miracle Month" of 1991 but four storm days produced acceptable seeding conditions. Six seeding flights were logged with two rated excellent, two logged as good, and one each rated fair and poor. April returned to semi-drought conditions with two flights rated fair on a single storm day.

Aircraft flights conducted during the total operational period of three months are listed in Table 2.

TABLE 2

ATMOSPHERICS INCORPORATED
SANTA CLARA PROJECT FLIGHT SUMMARY
1 FEBRUARY TO 30 APRIL 1992

Flt. No.	Date	Takeoff Time	Land Time	Flight Total (hrs)	'91/92 Total (hrs)	No. of Pyros	AgI (gms)	Seedability
1	02/01	0250	0505	2.2	2.2	17	340	good
2	02/06	1230	1330	1.0	3.2	1	20	poor
3	02/09	1605	1755	1.8	5.0	7	140	fair
4	02/09	1942	2205	2.4	7.4	23	460	good
5	02/11	2025	2355	3.5	10.9	30	600	excl
6	02/12	0140	0240	1.0	11.9	3	60	fair
7	02/13	0020	0120	1.0	12.9	6	120	poor
8	02/13	0315	0435	1.3	14.2	11	220	fair
9	02/14	1405	1505	1.0	15.2	1	20	poor
10	02/19	1510	1655	1.7	16.9	4	80	good
11	02/19	1805	1930	1.4	18.3	3	60	fair
12	03/05	0855	1045	1.8	20.1	4	80	fair
13	03/05	1140	1410	2.5	22.6	18	360	excl
14	03/14	0940	1110	1.5	24.1	8	160	good
15	03/20	0855	0948	0.9	25.0	1	20	poor
16	03/20	1600	1645	0.7	25.7	6	120	excl
17	03/22	1625	1835	2.2	27.9	8	160	good
18	04/12	0825	0945	1.3	29.2	5	100	fair
19	04/12	1335	1540	2.1	31.3	7	140	fair
TOTALS FOR 1991-1992 SEASON:				---	31.3	163	3,260	

5.0 EVALUATIONS

Scientific evaluations of cloud seeding programs are extremely difficult and expensive because the relatively small effects from the application of this technology are mixed and buried within the extreme variability of the natural precipitation processes. There are a few basic field experiments which can produce such striking visual results that the cause is not in doubt. Virga and precipitation cores from a seeded small cumulus cell in a field of similar cumulus developments are obvious examples of artificially induced precipitation. Seeding tracks of unusual design in supercooled stratus, with the attendant rain or snow trails below these cloud decks, are further examples of unquestioned visual results. However, when the clouds and storms are upscaled to larger and more complex systems, the visual and measurement opportunities disappear within the massive processes. Hence, a reasonable evaluation of any cloud seeding program would seem a desperate playing field. It is not necessarily the case as long as the term "reasonable" is invoked.

Operational programs such as the one conducted by Atmospherics Incorporated for SCVWD are not scientific experiments! Consequently, the SCVWD program conducted in the 1992 season differs in an obvious fashion from experimental programs. Where certain hypotheses are to be tested, the general procedure used in scientific experimental programs is randomization. In this process, single clouds or entire storm systems, which fall within certain specified criteria, are either treated or untreated according to instructions passed to the operator without his prior knowledge. After many treated and untreated cases are obtained, they are subjected to statistical tests in order to show whether or not any differences may be the results of treatment.

Unless rather extensive and sometimes unrealistic results from seeding are anticipated, the large number of samples required becomes impractical. Perhaps as a result of unrealistic expectations, and an under-estimate of the natural variability in clouds and precipitation, results from a few previous randomized cloud seeding experiments have been mixed. Some have indicated strong positive results, some have been indeterminate. However, it should be thoroughly appreciated that economically important increases in precipitation amounting to 10% or more may be incapable of precise detection within practical time limits because of statistical and natural restraints, and perhaps because statistical methodology may not reasonably address the divergent nature of clouds and storm systems!

In the case of the SCVWD program, Atmospherics Incorporated was asked to bring a technology to a specific area and, because of diminishing water supplies, apply this technology to whatever clouds were suitable for treatment. It should be emphasized the technology is not new in California, having been applied on several programs for more than 40 years. All seedable clouds were treated according to predesignated criteria. The philosophy of this operational undertaking was to apply a cloud seeding technology which had been successfully demonstrated in a number of climatologically similar areas in California and other locations in the world. Because the program was designed as a purely operational effort, it is not possible to **precisely** identify with scientific precision the results from the cloud seeding. This difficulty will always be present as long as the program is one

which is designed solely to produce additional precipitation by taking advantage of every suitable cloud condition without the inclusion of randomization or an expensive airborne and ground-based measurement program.

As originally stated, it is unlikely that any non-randomized short term program could generate data in a few months which would demonstrate statistically significant results at a high confidence level. The period of operation is far too short and the numbers of seeding cases much too limited. However, the SCVWD program has produced a reasonable number of optimum seeding conditions and positive results are highly suggestive in these cases, particularly those results suggested by both the radar data and the actual snow/rainfall distribution.

5.1 Radar Data Analysis

A basic examination of the radar data has been completed for the SCVWD cloud seeding program conducted during the 1992 season. Various characteristics of radar echoes associated with both the seeded clouds and simultaneously occurring non-seeded clouds adjacent to the target area have been examined. Radar echo characteristics of primary interest in this study were, (1) maximum echo intensity, (2) maximum echo height, (3) duration of precipitation period, and (4) area coverage of precipitation events. These particular characteristics are ones closely related to the actual changes in precipitation at ground-level and represent strong "indicators" within our physical studies.

During the February-April period in 1992, a total of some 296 precipitation echoes were plotted on 116 radar overlays. Many of these precipitation echoes were in areas well beyond the seeding effects. We have now analyzed essentially all the available radar data for possible differences between seeded echoes which affected the target area and the non-seeded precipitation echoes in adjacent areas. The results from this investigation are summarized in the following Table 3.

TABLE 3.

ANALYSIS OF RADAR ECHO CHARACTERISTICS

CATEGORY	Percentage greater than the Non-seeded Echoes (Average)
	1992 (Feb-Apr)
Maximum echo intensity	5%
Maximum echo height	23%
Duration of precipitation period	36%
Areal coverage	41%

Using the standard radar reflectivity equations applied to these data there is a strong indication the cloud seeding program operated during the 1992 period did produce significant increases in precipitation. If one extrapolates these radar echo characteristics to precipitation on the ground, an average apparent increase of 9% - 13% is a conservative estimate. In terms of the rainfall totals over the target area in 1992, this percentage increase would suggest nearly two inches of supplemental precipitation. An example of a radar depiction sequence is included as part of this section.

The eight attached radar depictions (Figures 5-12) show a sequence of precipitation echoes logged from 1100 to 1430 during the storm period on 5 March 1992. Figure 4 is a radar display base map which simply depicts the target boundary, and the location of the radar and aircraft within the operations area. Precipitation areas are shown hatched and represent the 26dB radar echo contour boundary. At the time of each overlay, precipitation was covering a much larger total area but the intensities were less than within the hatched areas. Following are some brief comments on each precipitation echo overlay.

Brief Comments Regarding the Radar Depictions of 5 March 1992:

1100: About one hour before the airborne seeding was activated, this radar depiction at 26dB attenuation shows five small precipitation areas scattered within and adjacent to the target area. It is important to understand that rainfall is in progress throughout much broader areas than shown on these radar depictions. The 26dB attenuation contour was chosen so certain ground clutter, light rainfall intensity areas and radar side-lobe echoes would not interfere with the depicted precipitation contour boundaries.

1130: This radar depiction shows continuing small scattered areas of precipitation about 30 minutes before seeding was initiated. About this time the most seedable portion of the overall storm system was moving toward the area from the southwest. A NW-SE oriented flight track some 8 nm miles southwest of the target boundary had already been chosen for the cloud seeding aircraft.

1200: The aircraft had been launched for a seeding flight some 20 minutes prior to this depiction. The cloud characteristics had now met all of the seedability criteria and seeding was initiated at the time of this depiction. The precipitation areas at 26dB are still scattered around the area but those along the chosen seeding flight track are in a high priority position for treatment.

1230: Seeding has now been in progress for about 30 minutes and immediately downwind from a portion of the flight track a large precipitation area at 26dB attenuation has evolved in the central part of the target. Seeding proceeds as other suitable cloud systems move toward the target area.

1300: This radar depiction shows the original seeded cloud volume in the north central part of the target, while a second echo downwind from the seeding flight track has moved into the southwestern portion. It is interesting that the orientation of these seeded areas is more or less parallel to the direction of the flight track.

1330: The major seeded precipitation echoes have now merged, forming over a much larger area than any of the 26dB attenuation echoes beyond the target boundary. These smaller echoes beyond the effect from seeding still remain randomly positioned and contain none of the characteristics of the seeded cloud volume. At this time, the height of the precipitation echo within the target area is some 2,000 ft. higher than any of the surrounding precipitation echoes. The radar meteorologist has just reported that storm characteristics southwest of the target area have now fallen below the seedability criteria.

1400: This radar depiction at 26dB attenuation shows the various precipitation areas some 10 minutes following termination of the airborne seeding. The large echo downwind from the seeding track is well oriented within the target area and has strong correspondence to the previous flight track. Precipitation echoes at 26dB attenuation, and beyond the effects from seeding, are still randomly scattered throughout the various areas and demonstrate essentially none of the remarkable characteristics of the seeded cloud volume. The radar meteorologist reports the storm system is continuing to weaken throughout the area southwest of the Anderson-Coyote target area.

1430: All seeding had been terminated about 40 minutes prior to this radar depiction. At this time, the general storm system had essentially moved beyond the target boundary. However, a portion of the seeded area is still showing a significant precipitation echo at 26dB attenuation. No other precipitation echoes at this time and intensity beyond the target boundary were measured by the radar. Lighter intensity precipitation echoes were noted in scattered areas within and adjacent to the target boundary but not shown in this depiction.

FIGURE 4.

RADAR DISPLAY BASE MAP

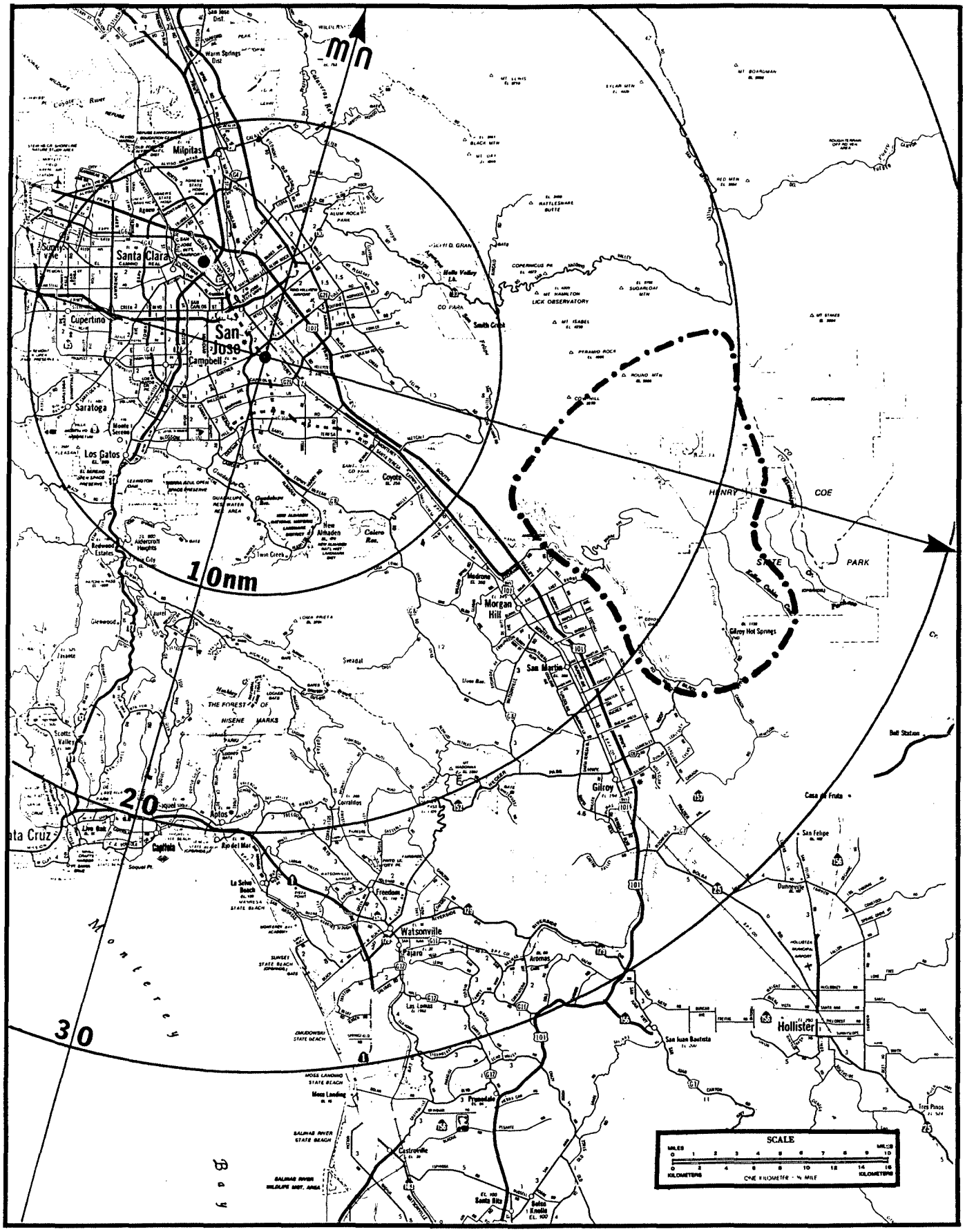


FIGURE 5.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

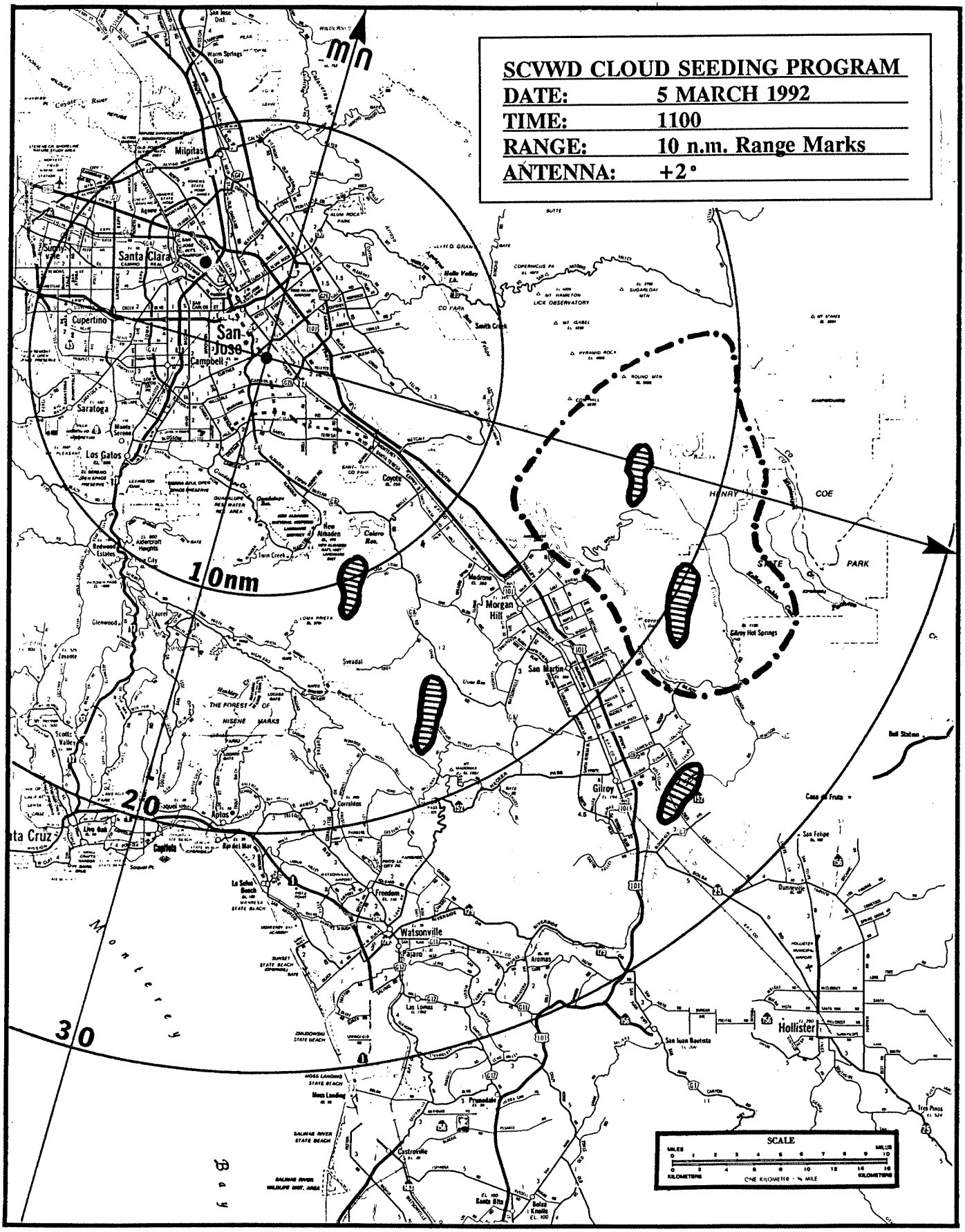


FIGURE 6

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

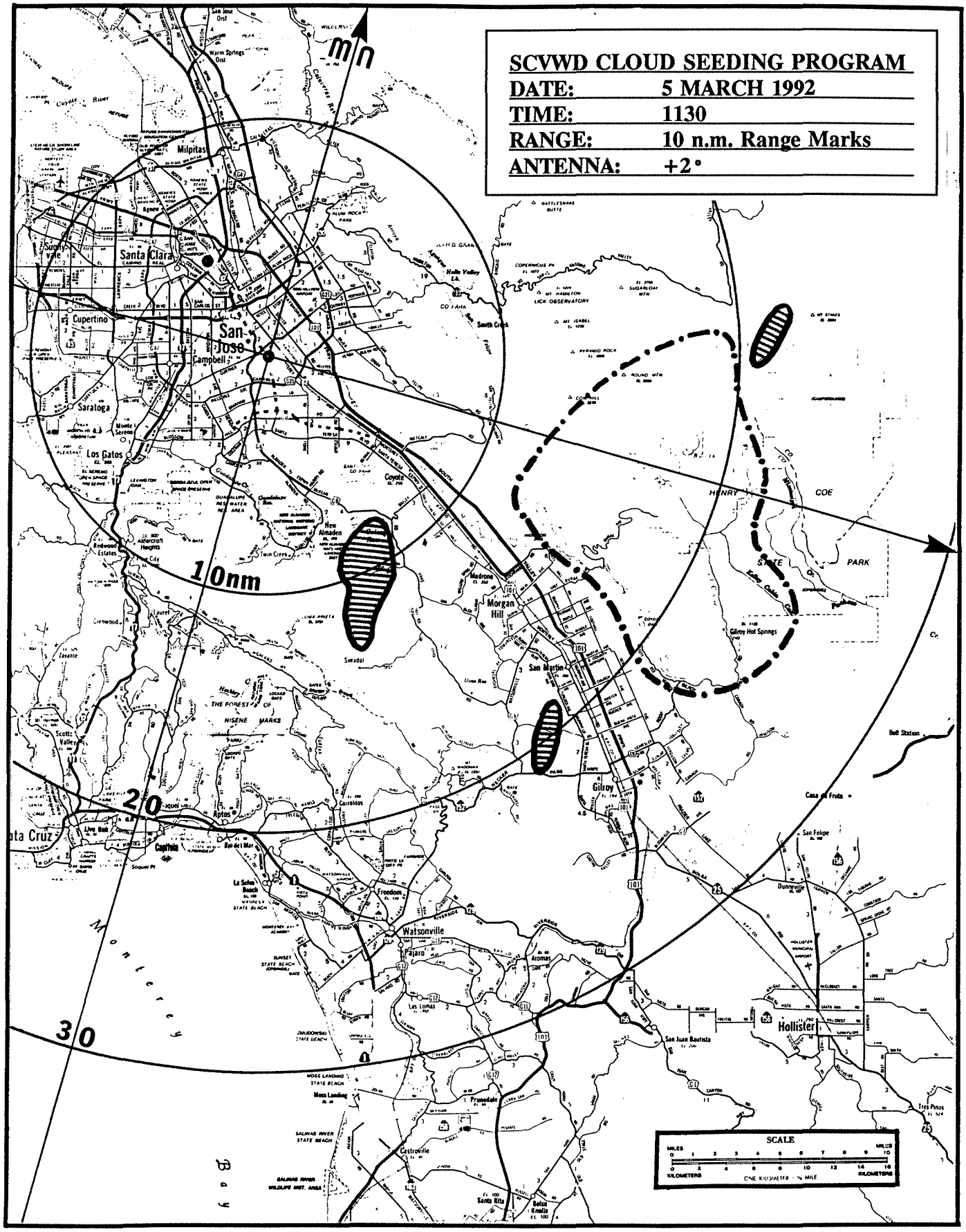


FIGURE 7.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

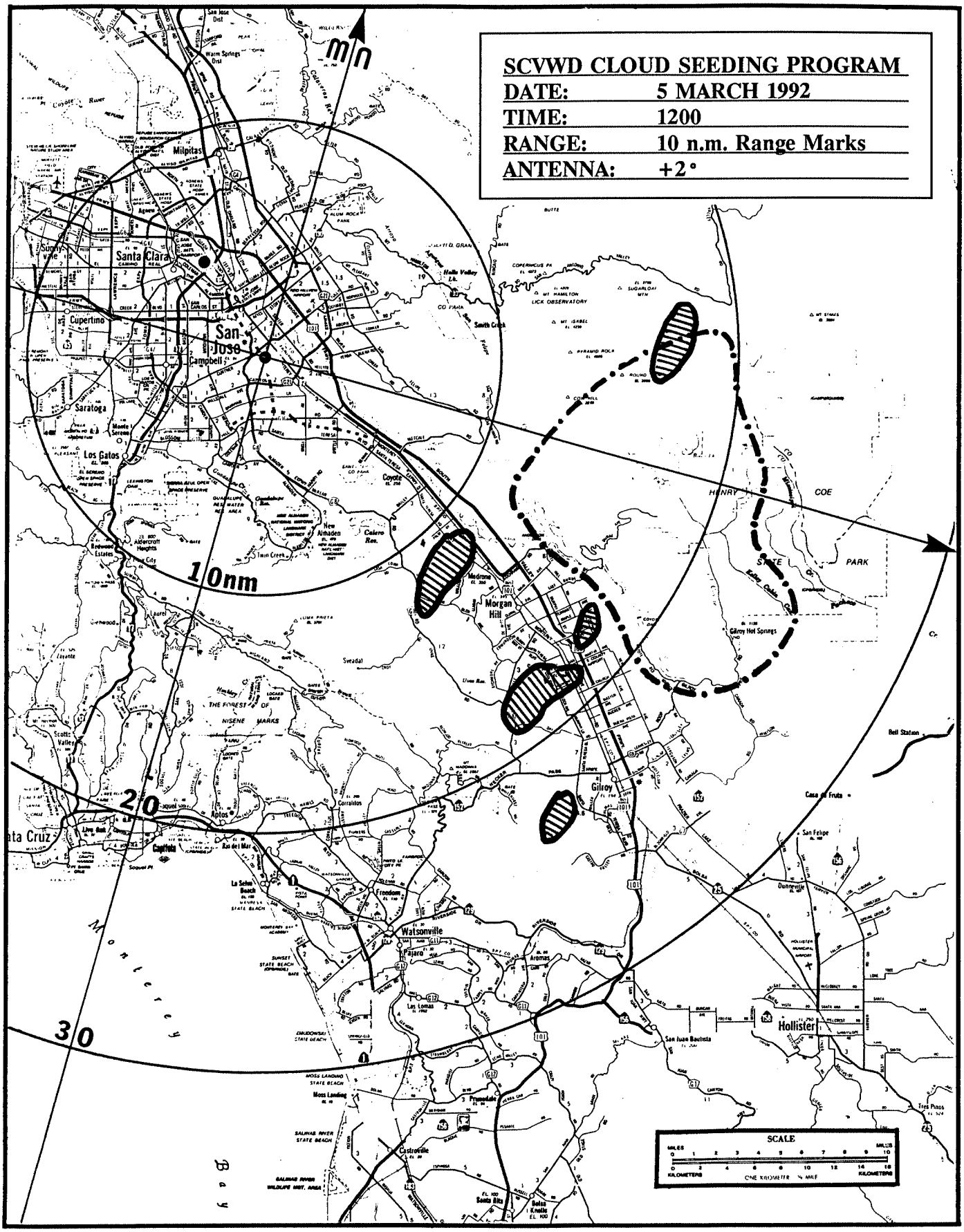


FIGURE 8.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

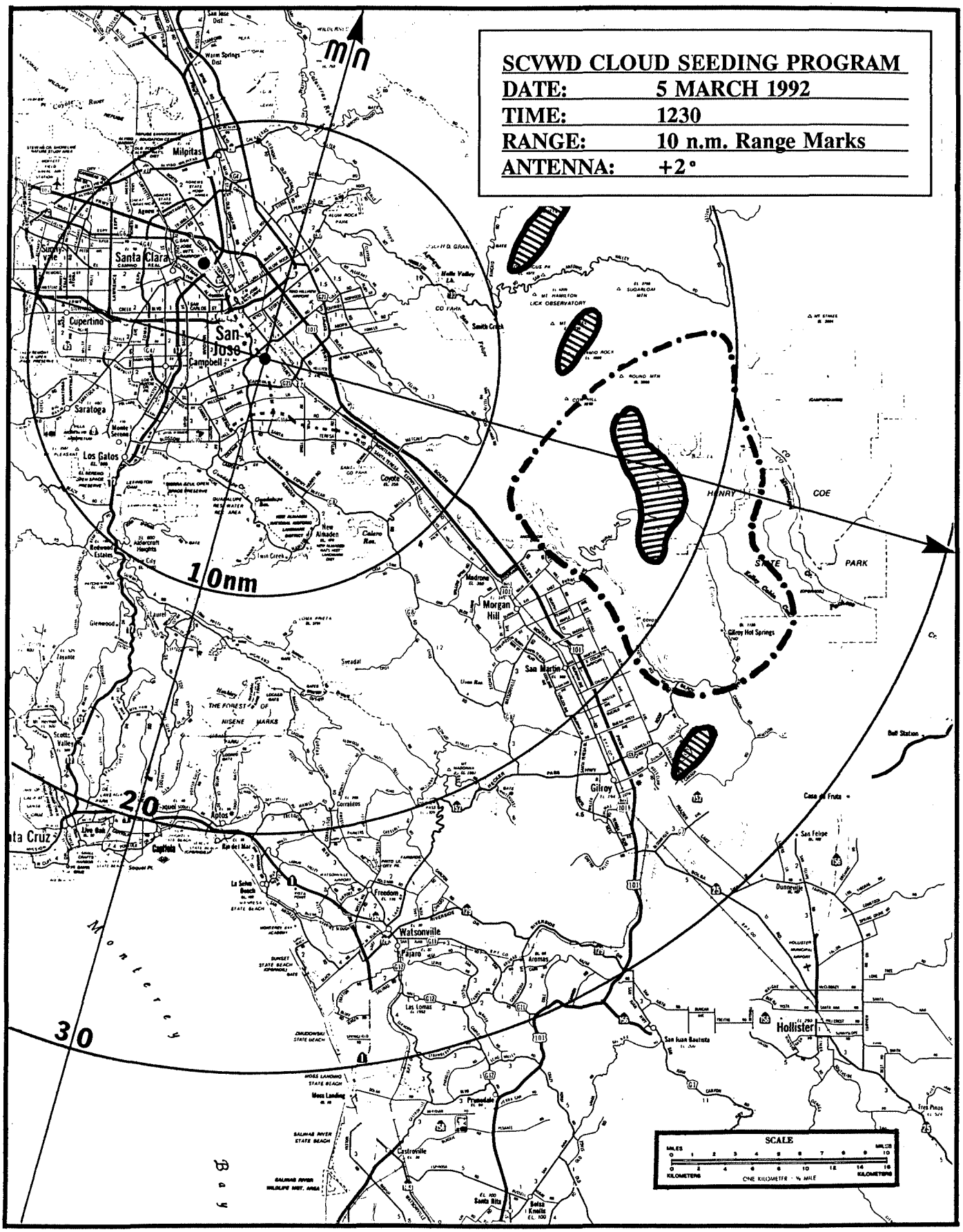


FIGURE 9.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

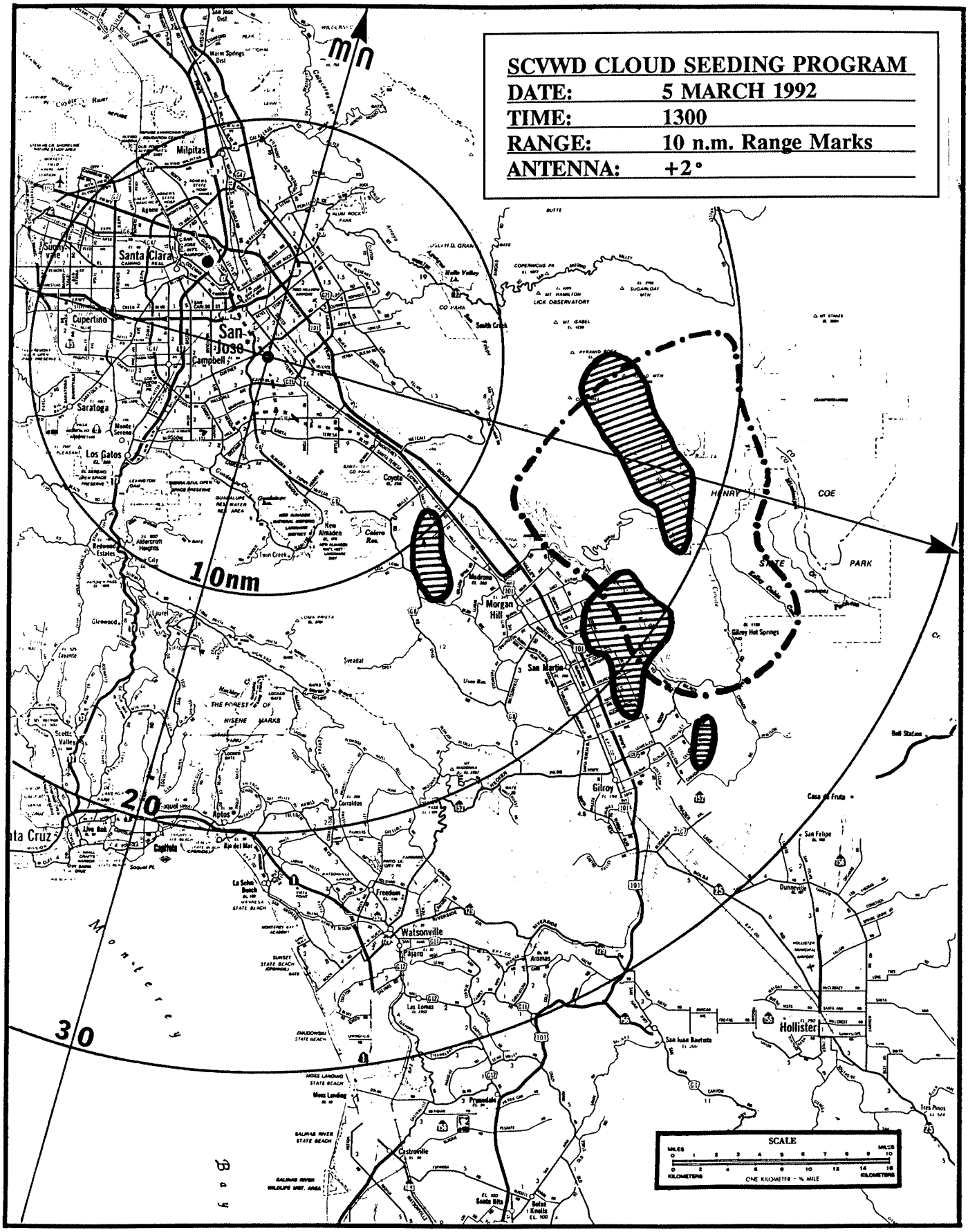


FIGURE 10.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

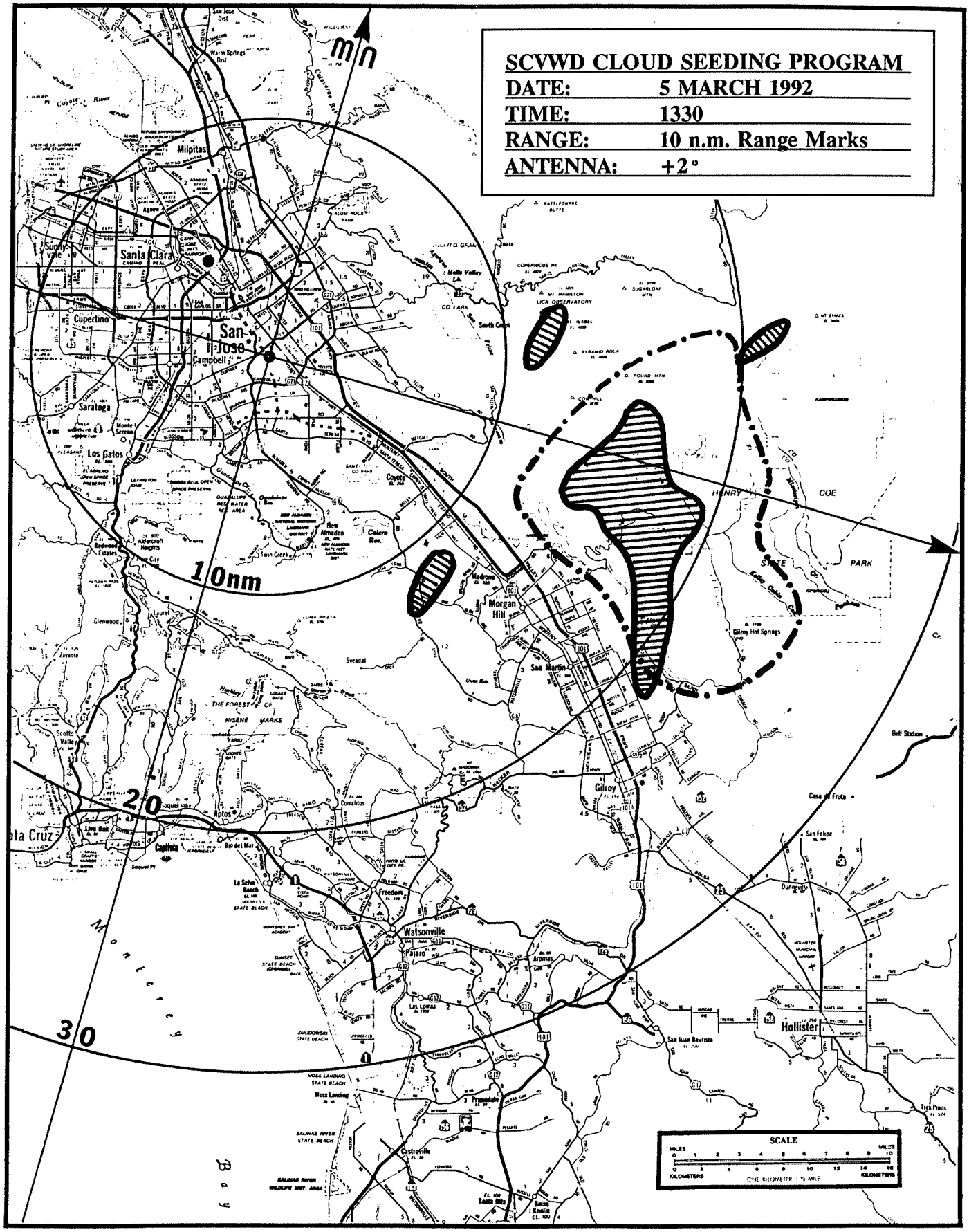


FIGURE 11.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB

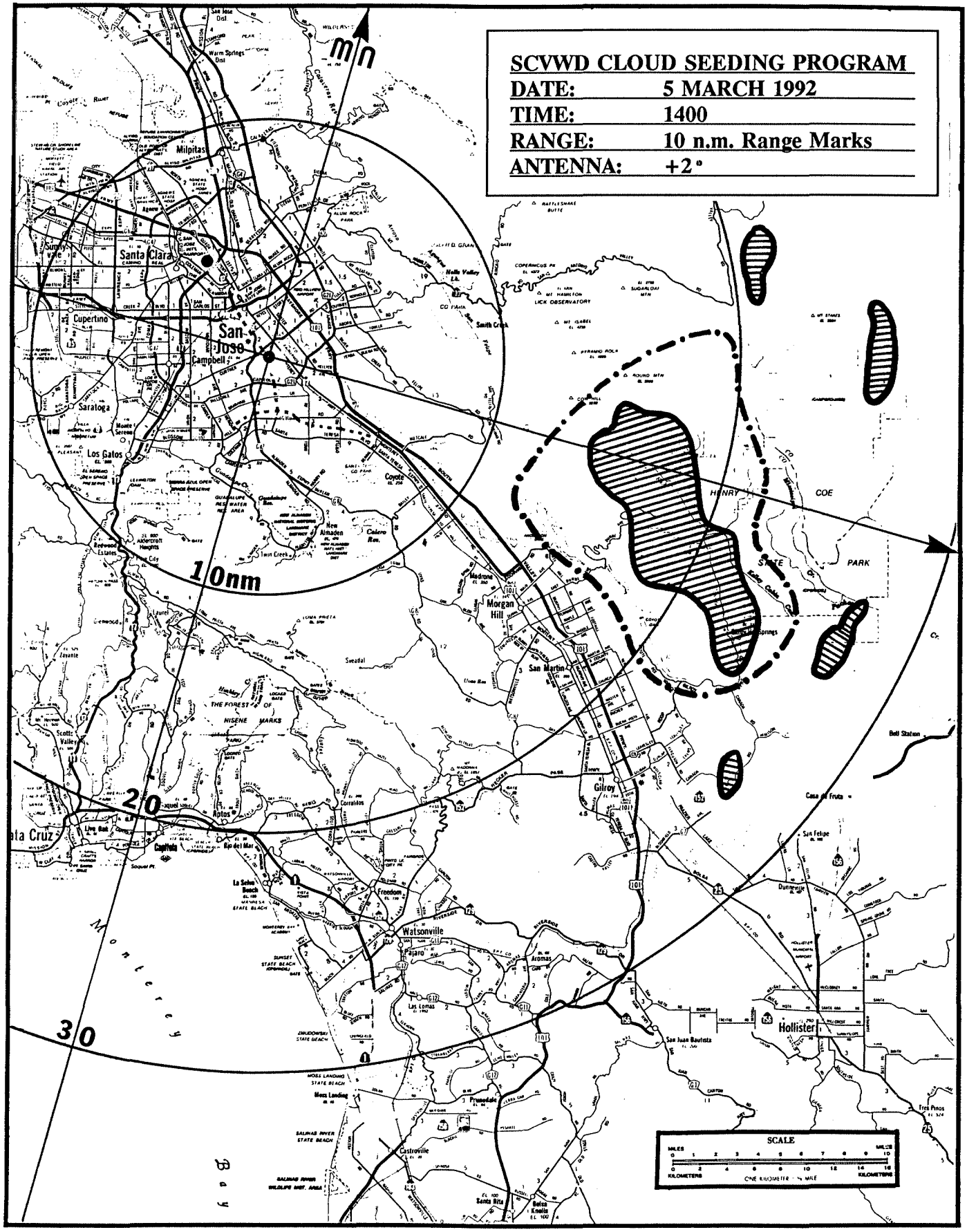
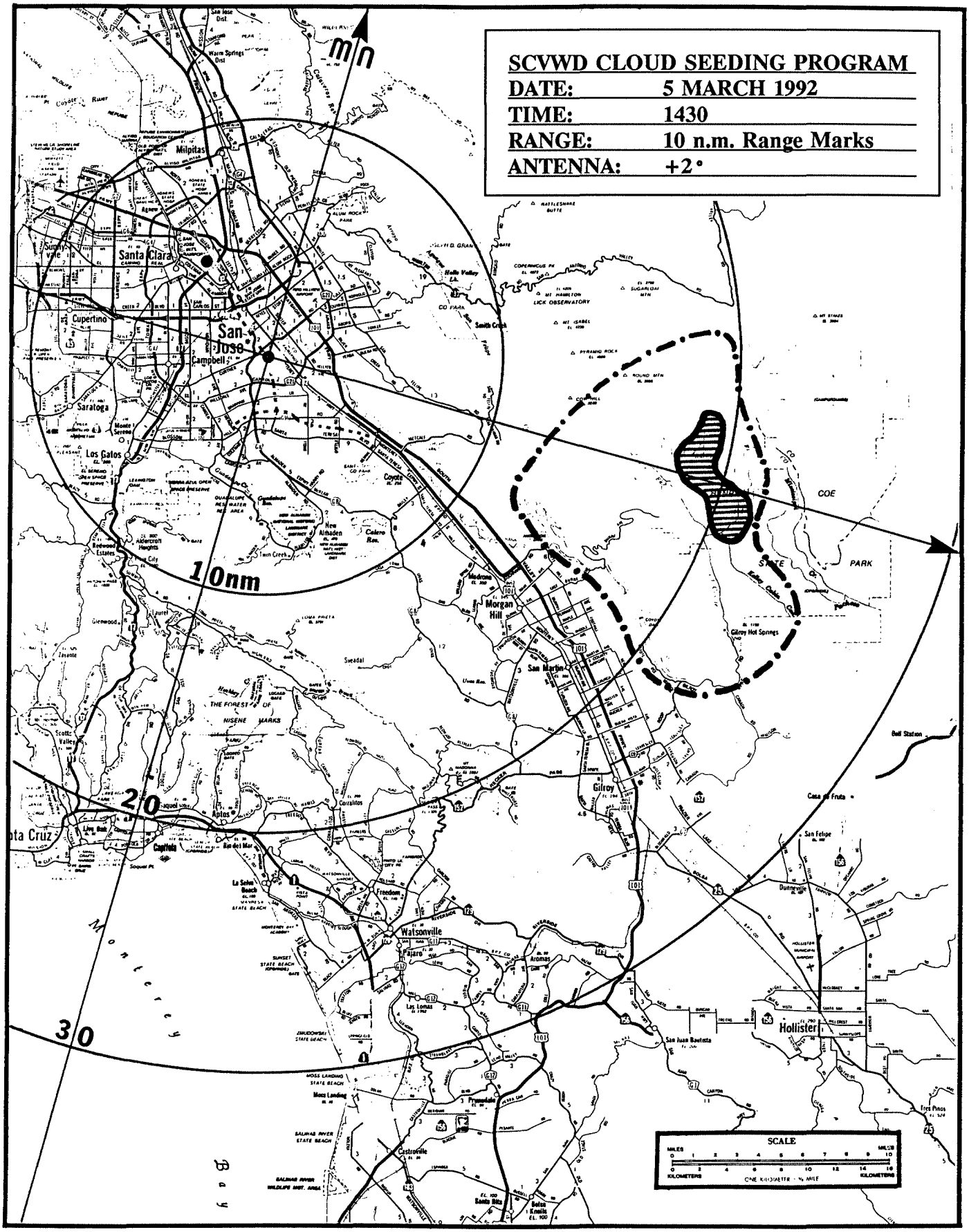


FIGURE 12.

RADAR DEPICTION - PRECIPITATION AREAS AT 26dB



5.2 Rainfall and Streamflow Data

Serious analysis of rainfall amounts and distribution over any size area require the following:

A. Precipitation gages must be of standard configuration (tipping bucket, weighing, etc.) with a routine maintenance and calibration procedure religiously invoked. Periodic visitations to each gage should not exceed 30 days, even if the gages are recording or remote reporting types.

B. The density of gages within an area must be high enough to represent with reasonable resolution the rainfall over that total area of interest.

C. The importance of careful gage site selection cannot be overemphasized. Because a raingage can only tell you something about the rainfall at a specific location, the subsequent records can only be an "index" of rainfall over the surrounding area. Therefore, the gage sites must be chosen under certain criteria set forth to provide reasonable assurance of this representative "index". For comprehensive statistical work, the rainfall record at any location must be at least 15 years duration with monthly totals a minimum requirement. Daily amounts are preferable and these should be true daily figures, not composites of rainfall during the previous two or three days.

Fortunately, the precipitation gage network within and adjacent to the Anderson-Coyote drainage area does meet most of the minimum criteria necessary to assure some reasonable information about the total rainfall distribution and amounts. The major area of concern is simply that most of the present gages are located more or less near the perimeter or well beyond the target boundary. Very few are located in areas where rainfall totals are most important for total assessment of the cloud seeding program.

The radar data summarized in the previous section is a case in point. The rain areas at 26dB attenuation are, in many cases, positioned over locations where there are no gages. As a consequence, it is not possible to a provide a precise "ground truth" analysis in regards the radar information on rainfall intensity, area coverage, or calculated total amounts.

About the only thing we can really say in regards the radar data from 5 March 1992 and measured rainfall at ground level, is simply that corresponding rainfall in significant amounts was recorded at many of the stations. Further, those stations which might be expected to receive a positive effect based on flight track orientation and model predicted fallout trajectories did, in fact, receive significant rainfall. For example, total rainfall amounts in some of the target and control gages before and after the seeding events, including percentage changes, are shown in Table 4. Further discussion at this time on precipitation distribution would be pure speculation.

Our initial investigations of streamflow and reservoir storage has indicated that the watershed characteristics, runoff efficiencies, reservoir storage changes, and general water transfer policies, are not fully understood by Atmospherics Incorporated. These preliminary studies suggest certain positive results but the work is far from complete. As in the area of

ongoing precipitation analyses, we feel that further speculation "water in the reservoir" is certainly tempting but the value would be questionable.

Continuing studies are in progress on both precipitation and hydrologic features. Results from these studies will be put forward as the cloud seeding program evolves.

TABLE 4.

TARGET AND CONTROL PRECIPITATION COMPARISONS
(Seeding Event of 5 March 1992)

STATIONS	Rainfall Totals Before Seeding (1027 PST)	Rainfall Totals After Seeding (1402 PST)	Percent Change
Target			
Coyote Reservoir	0.24	0.59	146%
Anderson Reservoir	0.16	0.43	169%
Coe Park	0.31	0.94	203%
Cow Ridge	0.28	0.75	168%
UTC	0.24	0.51	113%
Control			
Loma Prieta	0.67	1.30	94%
Mt. Umunhum	0.75	1.26	68%
Lexington Reservoir	0.75	0.94	25%
Uvas Reservoir	0.28	0.59	110%
Uvas Park	0.71	1.46	105%

(Note: A strong expression of appreciation goes to the entire Basic Data Group at SCVWD who performed an extraordinary service in providing timely precipitation, reservoir storage and general meteorological data which greatly assisted both the project operations and our understanding of the relationship between various atmospheric processes and rainfall at ground level).

6.0 CONCLUSIONS

Seedable clouds and storm systems were logged on 13 days during the February-April operational season in 1992. Seeding was actually accomplished on each of the 13 days. The program was under suspension on one additional day because of an NWS "Flash Flood Warning" when two additional flights would have been conducted in the absence of this suspension. A few of the more significant conclusions can be listed as follows:

- Based at the Santa Clara Communications Center, the radar could "see" with considerable resolution the cloud and storm characteristics over, and adjacent to, the target area during the 1992 season. These radar data have provided inputs to both the real-time operational aspects and subsequent preliminary evaluations.

- Cloud seeding aircraft continue to fly and properly deliver seeding material in this operational area where the mix of military, commercial and private aircraft occasionally produce a crowded air space. The Federal Aviation Administration provides an excellent cooperative spirit in assisting the flight activities of this program.

- Supercooled liquid water, a necessary ingredient for successful cloud seeding programs, was found to exist in rather high concentrations at temperatures warmer than -12 °C. This observation continues to suggest highly seedable conditions, at least during some portion of the storm periods which move through the area.

- The ability to enhance the natural precipitation processes seems apparent from the seeding events logged throughout this season when seedability was rated good. Of particular importance was the observation that, based on radar data and ground observations, portions of the seeded cloud volumes within the overall storm systems reached higher altitudes, were somewhat more intense for short periods, covered larger areas, and lasted for longer time periods than non-seeded clouds and storm systems in adjacent areas assumed not affected by the program.

- Significant evaluations still remain the most difficult aspect of any weather resources management program. Further study of existing streamflow measurement sites and historic records, plus in-depth investigation of precipitation records, remain in progress by AI staff and may illuminate some useful data for future evaluations. Based on this first season of operations we are moving toward a higher level of precision in our ability to identify the amount of additional "water in the reservoir" produced by the seeding events. The data analyses conducted during this recent study strongly suggest that positive effects in the range of 9% to 13% additional precipitation are real and beneficial.

- From a basic climatological point of view, the data obtained during the 1992 season support the notion that enough suitable clouds and storm systems move across the Anderson and Coyote watersheds to confirm the viability of this technology if applied during a longer November-April period in the future.

7.0 RECOMMENDATIONS

Based on the conclusions drawn from operations of this project during the past season, a few recommendations seem appropriate.

A. Equipment

- The turbocharged twin-engine Piper Aztec aircraft supplied adequate and safe flight characteristics during the seeding missions. There are no cases where missions were curtailed because of limited aircraft performance.

  Recommend: The Piper Aztec, or similar type of light twin aircraft, be retained as the primary delivery system for nucleating materials. It would be useful to add one or two basic meteorological or cloud physics instruments to the aircraft if the program is intended to run for more than another year or two.

- The 5cm (C-band) weather radar system provided adequate high resolution data for both the normal program operation as well as inputs to the evaluation of results from longer range programs.

  Recommend: The 5cm radar system be retained as the necessary component for storm monitoring, launch of seeding aircraft, inputs to seeding missions in progress, and as one of the primary sources of information for evaluations. An even better location for the radar system may be available and it would be useful to investigate this possibility.

B. Meteorological Data Acquisition

- Assessment of the various weather elements and organizing a detailed daily forecast from head office in Fresno was a satisfactory method for providing adequate inputs to the radar meteorologist operating from the Santa Clara County Communications site during this past season. At this time, it does not appear an installation of a full satellite weather data acquisition system at the radar site would be worth the additional expense.

  Recommend: The present weather data acquisition method be retained as the primary source of initial information necessary to direct the program.

- As in the case of most operational areas where cloud seeding programs are in progress, there is a minimum network of precipitation gages. The precipitation records serve an important role in evaluations, precipitation distribution studies, and hydrologic investigations.

  Recommend: Consider the procurement and installation of three or four additional recording snow/rain gages to be used as data sources for future cloud seeding evaluations as well as data inputs to the SCVWD water resources management studies.

C. Models

- The use of computerized models which provide guidance to the projected dispersion of seeding materials is always a part of the present cloud seeding technology. However, these models are limited by terrain features, real-time atmospheric measurements within and upwind from the operations area, as well as the variable effects from the microphysical processes of ice crystal formation, growth, melt rates, and fallout to ground level.

  Recommend: The use and trials of computerized guidance models be continued as a part of continuing program improvements. The on-site use of available small desktop or laptop computers be considered for real-time model use and data processing during future project operations.

D. Evaluations

- Significant evaluations are the most difficult and expensive aspects of any cloud seeding program. It has been estimated that the cost of in-depth evaluations can be four or five times the cost of the basic operation. However, some type of evaluation procedure is necessary to determine the approximate benefit/cost relationships at some reasonable level of probability.

  Recommend: Evaluation studies be continued with the use of available precipitation figures, radar data, available streamflow information, reservoir storage, and other data sources which may be useful to the program goals. These investigations should be expanded as time, personnel and budgets allow.

- The results from this initial program are encouraging. The preliminary evidence strongly suggests this technology applied to the Anderson and Coyote drainage basins is viable, and has produced inexpensive supplemental high quality water.

  Recommend: Based on the experience and apparent results associated with this important initial project, and reacting responsibly to the present drought conditions, establish a longer term operational program to be active during the six-month periods of November through April in each of the next three years, 1992/93, 1993/94 and 1994/95.

8.0 APPENDICES

8.1 HISTORIC QUOTATIONS ON EVALUATIONS

8.2 GLOSSARY OF TERMS

8.3 PROGRAMS IN CALIFORNIA - 1991/92 SEASON

8.4 HELICOPTER FIELD TRIP - 27 FEBRUARY 1992

8.1 HISTORIC QUOTATIONS ON EVALUATIONS

Cloud seeding programs designed to augment precipitation by enhancing the natural precipitation processes began in the late 1940's following the early discoveries of Irving Langmuir, Vincent Schaefer and Bernard Vonnegut, a group of dedicated scientists working at the General Electric Research Laboratory in Schenectedy, New York. Today there are more than 20 programs active in California, substantial programs in six other states, and a broad range of programs in 40 additional countries. From the serious and extensive evaluations of many cloud seeding programs, a few examples of the conclusions are presented in the following quotations from a cross section of historic publications.

A. **Cloud Seeding Operations in the Bishop Creek, California, Watershed,** Ferguson Hall (U.S. Weather Bureau), Thomas J. Henderson and Stuart A. Cundiff (California Electric Power Company), Research Paper No 36, U.S. Dept. of Commerce, Washington, DC, Jan. 1953.

> *Comparison of the annual runoff from the seeded watershed with that from adjacent areas for the three years 1948, 1949 and 1950 showed an average positive departure significant at the 5% level. From the same analysis it is estimated that the average annual flow during the three-year period was augmented by 9%.*

B. **Final report of the Advisory Committee on Weather Control, Vol, II,** Report prepared for the President of the United States, Howard T. Orville, Chairman, Washington, DC, December 31, 1957.

> *A major result of all the research by the Advisory Committee's statistical group is the preponderant evidence that cloud seeding has produced an increase in the precipitation from the orographic and West Coast project classes by between 10% and 15%.*

C. **Weather and Climate Modification,** Report of the Special Commission on Weather Modification, National Science Foundation, Washington, DC, Dec. 20, 1965.

> *For the past 10 years the Kings River Conservation District has supported a cloud seeding program by Atmospherics Incorporated in the Kings River drainage area on the western slopes of the Sierra Nevada Range in California. A grant from the National Science Foundation provided for additional measurements for study of cloud physics and precipitation. Recent analysis of the data indicates an average 6.1% increase in runoff in the drainage area due to seeding for the period. This supports preliminary results of the research study by Colorado State University in the area of Climax, Colorado, and of other commercial seeding operations, extending over shorter periods of time, that seeding can give a moderate increase in precipitation in orographic situations.*

D. **Weather and Climate Modification, Vol. II, Research and Development,** Final report of the Panel on Weather and Climate Modification to the National Academy of Sciences, Publication No. 1350, Washington, DC, 1966.

In all evaluations of 41 project-seasons, the test variates were seasonal watershed runoff values, obtained from U.S. Geological Survey records, with regressions based on nearby control watersheds for which runoff values correlated strongly (order of r = 0.90) with the target runoff. Project durations range from 8 to 14 years. The duration-weighted average runoff increase of the four test projects is about 12%, and it is apparent that their combined significance level is such that natural variability is not a likely explanation for these increases.

E. **Weather and Climate Modification, Problems and Progress,** Committee on Atmospheric Sciences, National Research Council, National Academy of Sciences, Washington, DC, 1973.

Since 1955 there has been a continuing project of cloud seeding over the drainage basin of the Kings River in California that is designed to increase precipitation and runoff. The program has been conducted by Atmospherics Incorporated of Fresno, California, which seeded clouds over a 1,600 mi^2 target area above Pine Flat Dam. The runoff from the target basin has been compared with runoff predicted from a multiple regression equation depending on the runoff from two control basins. Overall, the runoff during the 17 years of seeding has been about 6% greater than was predicted by the regression equation.

F. **Weather and Climate Modification, Problems and Progress,** Committee on Atmospheric Sciences, National Research Council, National Academy of Sciences, Washington, DC, 1973.

Seeding of orographic clouds has been carried out systematically in the Rocky Mountains of Colorado under the leadership of Colorado State University. The experiment subdivides into four separate efforts. These are: (1) the Climax Experiment I from 1960 to 1965, (2) the Climax Experiment II from 1965 to 1970, (3) the Wolf Creek Pass Experiment from 1964 to 1969, and (4) the Monarch Pass Experiment from 1964 to 1969. These programs were randomized over an experimental time unit of 24 hours. Significant differences between seeded and non-seeded events were observed and the results support expected changes predicted by the physical model of wintertime orographic precipitation processes. Ratios of seeded to non-seeded mean precipitation amounts for the 500 mb temperature category of -11°C to -20°C were found to be: Climax I (1.85), Climax II (1.74), Monarch (1.84), and Wolf Creek (1.90).

G. **Weather and Climate Modification, Problems and Progress,** Committee on Atmospheric Sciences, National Research Council, National Academy of Sciences, Washington, DC, 1973.

Cumulus clouds over some of the high mountain watersheds of the Sierra Range in California were seeded during the summers of 1966, 1967 and 1968. The purposes of the program were to establish whether precipitation could be initiated and increased and whether runoff from the watersheds could be increased and to develop engineering concepts for use in cloud-seeding operations. Linear

regression equations were derived for predicting target-basin runoff knowing the runoff from the four control basins. The actual average runoff for the test cases was 55.7 A.F./sq.mi. compared with a predicted average runoff of 25.8 A.F./sq.mi. For all cases, the application of statistical methods yielded a significance level of 0.005.

H. **Weather and Climate Modification, Problems and Progress,** Committee on Atmospheric Sciences, National Research Council, National Academy of Sciences, Washington, DC, 1973.

The Pacific Gas and Electric Company has been engaged in cloud-seeding projects in the northern Sierra Nevada Mountains in California since 1953. It was decided in 1960 to initiate a randomized experiment involving the seeding of winter storms with silver iodide from ground generators. In establishing the results, two statistical methods were used, namely a regression analysis and covariance analysis. In the "cold westerly" storm category both methods of statistical analysis showed that the precipitation in the seeded area was greater by about 32% than that in the unseeded area and that this difference was significant at the 0.05 level.

I. **Weather and Climate Modification,** Edited by W.N. Hess, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, John Wiley and Sons, New York, 1974.

Summary of results of field experiments: A number of well conducted and carefully analyzed experiments of weather modification to augment orographic precipitation are giving results consistent with expectation from physical considerations of "cold" orographic cloud processes. It seems clear that for many orographic clouds with cloud top temperature at least in the range from about -10° C to around -20° C, a substantial weather modification potential exists and that this potential is being realized from artificial seeding.

J. **Weather and Climate Modification,** Edited by W.N. Hess, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, John Wiley and Sons, New York, 1974.

A cloud seeding experiment was started in Tasmania in 1964. It was intended to investigate the effects of seeding clouds with silver iodide smoke release from an aircraft on rainfall over a designated area. The first stage of this experiment took place in the four operational years 1964, 1966, 1968 and 1970. The preliminary result was that the rainfall on the target areas was increased by seeding during the autumn and winter, the effect being estimated as 15% to 20% at a satisfactory significance level. The value of this increase is much more than enough to justify the cost of the program.

K. **Cloud Seeding in Australia,** E.J. Smith, Weather and Climate Modification, John Wiley and Sons, New York, 1974.

Preliminary trials were first performed in which silver iodide smoke was released from an aircraft into single supercooled clouds with the intention of stimulating rain. The first fully randomized series of trials was undertaken. The results indicated that more rain fell from the seeded clouds than from the unseeded ones. There was very little likelihood that such a large difference could have arisen by chance, and the conclusion was drawn that the seeding had increased the rainfall. In these experiments the mean rainfall from a single seeded cloud exceeded that from an unseeded cloud by over 100 A.F.

L. **Modification of Meteorological Processes,** Y.K. Federov, Director, Hydrometeorological Service, Moscow, USSR, Weather and Climate Modification, John Wiley and Sons, New York, 1974.

Experiments to augment precipitation carried out in the USSR up to the present time have indicated that approximately 10 to 15% more water can be obtained by seeding. It is curious that this figure, about 10%, recurs practically unchanged in an enormous number of experiments carried out by different means in widely different regions.

M. **Report on National Cloud-Seeding Operation in Rhodesia during the 1974-1975 Period,** J.E. Stevens, The Journal of Weather Modification, Vol. 8, No. 1, Fresno, California, April 1976.

During this non-randomized operational program, a total of 688 of the 793 observed seedings produced an increase in cloud growth and rainfall. This represents a success rate of 88%. The research program has shown that on average a successful seeding produces approximately 120,000 tons of extra water.

N. **The Israeli Rainfall Enhancement Experiment - a Physical Overview,** Dr. Abe Gagin, Journal of Weather Modification, Vol 13, No. 1, Fresno, California, April 1981.

The earlier overall results of Experiment I, namely those indicating rainfall increases of the order of 15%, significant at the 2% level, have been confirmed in Experiment II, that is, a 13% increase at a 2.8% significance level.

O. **Weather Modification in Southeast Asia, 1966-1972,** E.M. Frisby, The Journal of Weather Modification,Vol. 14, No.1, Fresno, California, April 1982.

On 9 November 1966, the Commander-in-Chief (CINCPAC) reported that the test was completed. In 56 seedings, 85% of the clouds operated upon had reacted favorably and CINCPAC concluded that "cloud seeding to produce additional rain over infiltration routes in Laos could be used as a valuable tactical weapon" (Congress 1974). Since documentation of the Popeye Experiment had been adequate and results sufficiently positive, operations conducted on similar lines could be expected to produce similar results. The actual cloud seeding operation, affecting parts of Laos, North Vietnam, South Vietnam and Cambodia began on 20 May 1967 and continued through the appropriate months of each year (March-November) until 5 July 1972.

P. **Weather Modification by Cloud Seeding,** Arnett S. Dennis, International Geophysics Series, Vol. 24, Academic Press, 1980.

Evaluations of cloud seeding projects to increase precipitation from orographic storms of the western United States have generally given indications of increases in the target areas of the order of 10-15% of the precipitation which would have occurred naturally. The relative consistency of results from different projects is encouraging.

Q. **Precipitation Enhancement - A Scientific Challenge,** Edited by Roscoe Braham, Jr., Meteorological Monograph Vol. 21, No. 43, Published by the American Meteorological Society, December 1986.

The number of commercial cloud seeding operations greatly exceeds the number of research experiments. Typically, these operations were of short duration, had very limited measurement components and lacked randomization. Generally speaking, the results from individual commercial seeding operations could not be rigorously established. A few commercial operations, however, were repeated using the same methods and location over several consecutive seasons, thus contributing to a growing body of experiences. These experiences have led some scientists to believe that, under appropriate conditions, cloud seeding will produce useful effects.

8.2 GLOSSARY OF TERMS

ARTIFICIAL CLOUD NUCLEATION:

Release of artificial cloud condensation nuclei or artificial ice nuclei into the atmosphere to influence cloud formation or behavior. It is the most common form of cloud seeding.

CLOUD CONDENSATE:

Liquid water and ice present in clouds.

CLOUD CONDENSATION NUCLEUS:

Aerosol particle, normally hygroscopic and greater than 0.1 microns in diameter, which is likely to serve as a center of condensation in cloud formation.

CLOUD SEEDING:

Any technique carried out with the intent of adding substances to a cloud to alter its natural processes.

CLOUD TYPE:

Cloud conditions with distinctive physical characteristics (cloud depth, temperature, wind, stability, etc.) such that different types may have different responses to seeding.

CONTROL AREA:

Region that is selected for comparison purposes to evaluate cloud seeding effects in a target area. It is expected to be unaffected by the seeding project being evaluated.

CONVECTIVE CLOUD:

A cloud characterized by organized, fluid motion, usually upward away from the heat source in the central portion and downward at the outer edges. This term generally is interchangeable with cumulus clouds.

CUMULUS CLOUDS:

Massive cloud form usually with a flat base occurring at low or middle cloud elevations between 2,000 ft. and 15,000 ft. They have rounded outlines often piled up like mountains, commonly appearing in the early afternoon on warm days.

DYNAMIC EFFECT:

An enhancement of up and down drafts through the release of the latent heat of fusion when supercooled water droplets are frozen. The seeding rates to achieve a dynamic response are often high in an attempt to freeze a high percentage of the available liquid water.

ICE NUCLEUS:

Insoluble particle that serves as a freezing center for the formation of ice from water or from the vapor.

ICE PROCESS:

The process by which cloud particles grow large enough to fall out as precipitation due to the coexistence of ice and supercooled water particles. The ice particles can grow rapidly at the expense of the supercooled cloud droplets.

INADVERTENT WEATHER MODIFICATION:

The unintentional modification of the weather through some aspect of man's activities, such as the production of seeding agents from various industrial manufacturing processes.

MODELS:

A mathematical description of an atmospheric process used to predict the subsequent behavior of clouds and storm systems, or to establish the delivery points of seeding materials for appropriate targeting of effects.

NUCLEATION:

Any process through which a phase change of a substance to a more condensed state is initiated upon a nucleus. For example, supercooled liquid water to ice.

OPERATIONAL CLOUD SEEDING PROGRAMS:

Those seeding programs conducted for a specific purpose, such as enhancing the production of precipitation or decreasing hail damage within a target area.

OROGRAPHIC:

Of or relating to mountains, especially with respect to their location, distribution and accompanying phenomena.

OVER-SEEDING:

Originally, the creation by seeding by so many particles, either solid or liquid, that none of them would possess sufficient fall speed to reach the ground as precipitation. In recent years, any form of cloud seeding that diminishes total precipitation at the earth's surface.

PRECIPITATION EFFICIENCY:

The efficiency with which condensed water within a cloud is utilized to form particles that can fall out and reach the ground as precipitation. This is the ratio of precipitation that reaches the ground to the mass of cloud water available for the formation of precipitation.

PYROTECHNIC:

A flare type device that as it burns, produces silver iodide smoke particles which act as ice nuclei.

SEEDABILITY:

Property of a cloud or cloud system that makes it possible for additional precipitation to be obtained by artificial cloud nucleation or other weather modification techniques.

SEEDING CRITERIA:

A set of conditions established for a cloud seeding project that are designed to optimize the augmentation of precipitation. Typical indices used are cloud top temperature, windflow, atmospheric stability, and water content.

SEEDING HYPOTHESIS:

A statement of expectations which states certain assumptions and predicts an outcome in terms of a seeding effect given the specifics on a seeding project.

SILVER IODIDE:

In its most common form, a yellow salt of hexagonal crystal structure. It is widely used throughout the world in weather modification because of its properties as an ice nucleus.

SILVER IODIDE GENERATOR:

Device that produces tiny crystals of silver iodide for use as a cloud seeding agent.

STATIC CLOUD SEEDING:

Cloud seeding to alter the precipitation by changing the efficiency with which existing cloud water is converted into precipitation-size particles.

SUPERCOOLED LIQUID WATER:

Liquid water droplets in the atmosphere existing at temperatures colder than 32° F (0° C).

SUSPENSION CRITERIA:

Criteria developed for a specific cloud seeding project to avoid seeding during undesirable periods.

TARGET AREA:

The area within which the effects from seeding are intended, usually a fixed geographic area.

TARGETING:

Releasing artificial seeding material in a manner which allows adequate dispersion, interception of supercooled liquid water droplets, growth of ice crystals, and fallout of augmented precipitation in a specified area.

TURBULENCE:

Irregular atmospheric motion, especially when characterized by upward and downward currents.

EXTRA AREA EFFECTS:

The effects of cloud seeding hypothesized to occur in regions beyond the intended target area.

8.3 CLOUD SEEDING PROGRAMS IN CALIFORNIA

1991/92 SEASON

Program Designation	Sponsor	Operator
1. Lake Almanor	Pacific Gas & Electric	Pacific Gas & Electric
2. Feather River	Dept. of Water Resources	Dept. of Water Resources
3. Lake Berryessa	Solano Co. Water Agency	Atmospherics Incorporated
4. Tahoe-Truckee	Desert Research Institute	Desert Research Institute
5. Carson/Walker	Desert Research Institute	Atmospherics Incorporated
6. American River	Sacramento Muni. Utility Dist.	Sacramento Muni. Utility Dist.
7. Mokelumne River	Pacific Gas & Electric	Pacific Gas & Electric
8. Calaveras River	Stockton East Water Dist.	Atmospherics Incorporated
9. Tuolumne River	Turlock & Modesto Irrig. Dists.	Atmospherics Incorporated
10. Eastern Sierra	Dept. of Water and Power	Atmospherics Incorporated
11. San Joaquin River	Southern Calif. Edison Co.	North American Weather Conslts.
12. Kings River	Kings River Conservation Dist.	North American Weather Conslts.
13. Kaweah River	Kaweah Delta Water Cons. Dist.	Atmospherics Incorporated
14. Kern River	North Kern Water Storage Dist.	Atmospherics Incorporated
15. Monterey County	Monterey Co. Water Res. Agency	Atmospherics Incorporated
16. San Luis Obispo	City and County - SLO	Atmospherics Incorporated
17. Santa Barbara	Santa Barbara County	North American Weather Conslt.
18. San Gabriel	Los Angeles County	North American Weather Conslt.
19. San Diego	City of San Diego	Atmospherics Incorporated
20. Santa Clara County	Santa Clara Water Agency	Atmospherics Incorporated

8.4 HELICOPTER FIELD TRIP - SANTA CLARA VALLEY WATER DISTRICT

27 February 1992, Thursday
Aris Helicopter Services

The two-hour reconnaissance flight included six persons in an Aris supplied helicopter. These were Travis (pilot), Tom Henderson (AI radar meteorologist) and four persons from the Geology Section at SCVWD. The flight was initiated at Aris Helicopters on the San Jose Airport, with a subsequent quick stop at the SCVWD head office to take on the four staff members.

The flight proceeded to Lexington Reservoir about four miles southwest of the office area, then southeast about three miles to Lake Elsman. Various land surface conditions were noted, plus general conditions around these reservoir areas. The flight then moved eastward about nine miles to Anderson Reservoir where a circle of the lake was conducted for observations of slide areas, potential dangers from land/resident aspects, and the other general considerations of the water level and relevant lakeside conditions. Terrain features as related to windflow directions and velocities were also noted.

From Anderson Reservoir, the flight proceeded southeast about four miles to Coyote Reservoir where similar observations were made of the water conditions and various aspects of adjacent land/residence areas. Additionally, there was an excellent view of the canyons and ridge lines east of Coyote Reservoir. An overview of these reservoir areas from the air was particularly important to the operational aspects of the cloud seeding program.

From Coyote Reservoir the flight proceeded easterly with good views looking at the canyons and ridges. Upstream from the reservoir the stream bends north and the flight circled Gilroy Hot Springs allowing excellent coverage both upstream and downstream. The flight then moved south, intersecting Highway 152 at San Felipe Lake. Turning easterly toward Pacheco Pass the flight circled Pacheco Lake before moving north and northwest upstream Pacheco Creek into the Henry W. Coe State Park area. The flight then proceeded northwest along the ridge line which separates Upper Pacheco and Coyote Creeks. At the headwaters of Coyote Creek, the flight turned westerly back toward the Valley and the upper northwest arm of Anderson Reservoir. From here the flight was essentially a straight line back to the SCVWD office.

The air reconnaissance provided a better understanding of the total cloud seeding target area and the complex terrain features which strongly influence the flight track choices and fall-out trajectories of augmented precipitation particles. The airflow along and below each seeding track is modified by these terrain features in ways important to accurately targeting the effects.

Beyond these important considerations, the flight provided an excellent visual image of the relationship between the target area itself and the adjacent cities, rural areas, roadways and specific geographic features. This information is vital to a better understanding of the

relationship between radar permanent echoes and the moving radar echoes produced by precipitation located within the clouds and storm systems.

A note of thanks to Larry Wilson for organizing this reconnaissance effort which provided much interesting information important to the design, operation and evaluation of the present cloud seeding program.